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ABSTRACT

This module examines the basic properties of soil which have an influence on the success of land treatment of wastes. These relevant properties include soil texture, soil structure, permeability, infiltration, available water capacity, and cation exchange capacity. Biological, chemical and physical mechanisms work to remove and renovate wastes after their application to the soil. Wastes are removed physically through filtration by the soil and altered by dilution, either upon entering the groundwater or by augmentation in the soil with natural rainfall or snowmelt. Absorption and precipitation are the two main processes of chemical retention of wastes in soil. Potentially toxic elements and the macronutrients nitrogen and phosphorus are partially controlled by chemical mechanisms in soil. Biological mechanisms alter waste constituents in stages. Soil organisms decompose organic compounds. The soil's ability to handle wastes is limited by the loading of nitrogen, phosphorus, and water, the addition of potentially toxic materials, and its sodium adsorption ration. This module summarizes these limitations, identifying nitrogen as the major limiting factor in most situations. (Author/EB)

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Land Application of Wastes

An Educational Program

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LAND APPLICATION OF WASTES - AN EDUCATIONAL PROGRAM

The objective of this program is to increase the knowledge of engineers, scientists, waste management specialists and other practitioners in the concepts and principles needed to properly utilize the potential of land for the application of wastes. It is designed for individuals concerned with waste disposal alternatives for municipal, industrial, and agricultural wastes. The modules in this Program incorporate knowledge from sanitary and environmental engineering, agronomy, soil science, agricultural engineering, economics, and law.

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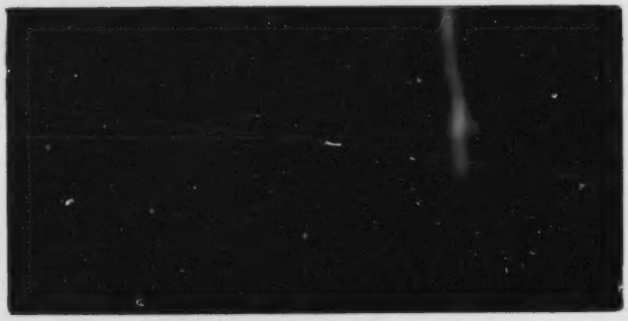

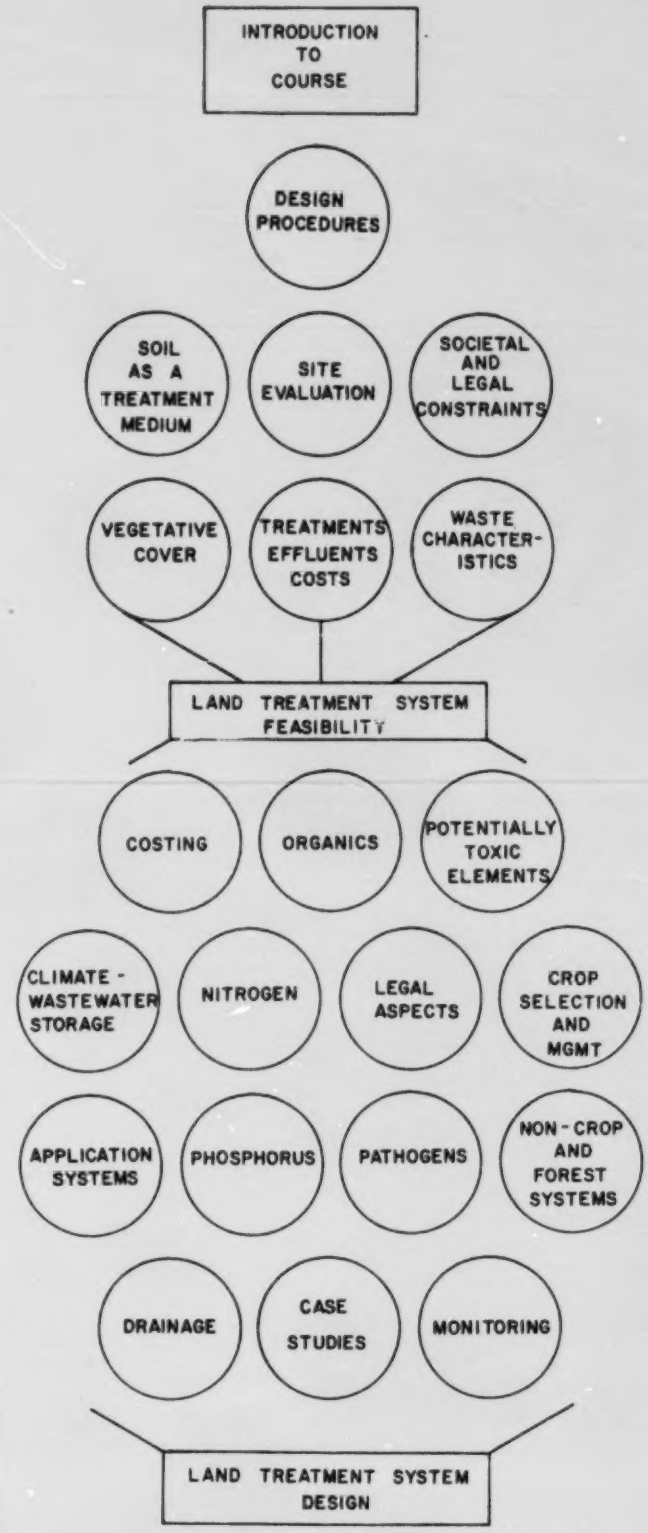

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SOIL AS A TREATMENT MEDIUM

Module 3

January, 1978

Summary

This module examines the basic properties of soil which have an influence on the success of land treatment of wastes. These relevant properties include soil texture, soil structure, permeability, infiltration, available water capacity, and cation exchange capacity.

Biological, chemical and physical mechanisms work to remove and renovate wastes after their application to the soil. Wastes are removed physically through filtration by the soil and altered by dilution, either upon entering the groundwater or by augmentation in the soil with natural rainfall or snowmelt. Filtration is limited by the potential of clogging soil pores with suspended solids. This clogging can be avoided by pretreatment and by allowing rest periods between applications.

Adsorption and precipitation are the two main processes of chemical retention of wastes in soil. Potentially toxic elements and the macronutrients nitrogen and phosphorus are partially controlled by chemical mechanisms in soil. The effectiveness of soil in the removal of waste constituents either by ion exchange or specific adsorption depends upon the contact between dissolved substances and the appropriate colloidal phases.

Biological mechanisms alter waste constituents in stages. Soil organisms decompose organic compounds. The rate at which organic matter decomposes and the exact nature of the intermediate and end products depend in part on the composition of the organic material being added in the form of wastes.

The soil's ability to handle wastes is limited by the loading of nitrogen, phosphorus, and water, the addition of potentially toxic materials, and its sodium adsorption ratio (SAR). This module summarizes these limitations, identifying nitrogen as the major limiting factor in most situations.

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Glossary

adsorption - the net effect of interactions between dissolved ions or compounds and the surfaces of clay and humus particles in soil; ion exchange is one type of adsorption process.

assimilation - the conversion of inorganic forms to organic forms within living tissue.

available water capacity (AWC) - that amount of water which is held in the soil between field capacity and permanent wilting point.

cation exchange capacity - a measure of the ability of a soil to retain positively charged ions called cations, generally serves as a rough index of all reactions occurring between charged pollutants and colloidal surfaces; CEC is a function of both the relative intensity of attraction between ions and colloidal solids and of the relative concentration of exchangeable ions present in the soil solution.

colloidal soil particles - clay and humus fractions of a soil characterized by their extremely small size ($\lesssim$ 0.002 mm), very high ratio of surface area to volume, and the presence of a negative electrical charge.

field capacity - the moisture content which a soil will hold against the force of gravity after it has drained for 48 hours following saturation; the amount of water retained by the micropores.

infiltration - the rate at which water enters the soil surface, expressed in inches per hour, influenced by both permeability and moisture content of the soil.

macropores and micropores - two types of individual pore spaces which generally occur in soils. Macropores characteristically allow the ready movement of air and percolating water; micropores greatly impede air and water movement, restricting it to slow capillary movement.

mineralization - the conversion of an element from an organic form to an inorganic form as a result of microbial decomposition.

overland flow - a method of land application whereby wastewater is applied onto gently sloping, relatively impermeable soil that has been planted to vegetation. Biological oxidation occurs as the wastewater flows over the ground and contacts the biota in the vegetative litter; also known as "grass infiltration" and "spray runoff."

permanent wilting point - the dividing point between the soil moisture that is extractable by plant roots and the moisture that is held too tightly for plant use.

permeability - the ease with which water and air are transmitted through the soil, determined by soil pore spaces; quantified in terms of the rate of water movement through a unit cross section of saturated soil in unit time; commonly expressed in inches per hour.

precipitation - formation of an insoluble or slowly soluble product from constituents that were originally in solution.

rapid infiltration system - a method of land application whereby large volumes of water are applied to the land, infiltrate the surface, and percolate through the soil pores; suitable for soils with high permeability.

regolith - the unconsolidated mantle of earth above the bedrock resulting from weathering of the underlying rock and/or deposition of material transported by gravity, wind, water, or ice.

specific adsorption - the retention of certain cations and anions so tightly by the soil that they are not exchangeable with other cations and anions. Specific adsorption occurs between ions or compounds in solution and the solid colloidal phase.

sodium adsorption ratio (SAR) - a ratio of specific available cations in the soil solution which indicates if the accumulation of sodium in the soil exchange complex will lead to a degradation of soil structure and thus a sharp reduction in infiltration and permeability rates. The formula for SAR is:

$$SAR = \frac{[Na^{+1}]}{\left(\frac{[Ca^{+2}] + [Mg^{+2}]}{2}\right)^{0.5}}$$

soil - to a soil scientist, soil is the upper portion of the regolith which has been intensely altered by living organisms and climate, giving rise to distinct horizontal layers called horizons. In waste treatment, soil refers to the entire regolith.

soil aggregates - clumps of soil particles which form units that range from weak to stable, small to large, and simple to complex.

soil structure - the organization of individual particles into clumps or aggregates.

soil texture - the coarseness or fineness of the individual mineral particles in soil.

Objectives

After completing this module, the participant should be able to do the following:

1. Describe the basic properties of the soil including texture, structure, permeability, infiltration, available water capacity, and cation exchange capacity. Explain how each property affects the soil's ability to renovate waste constituents.

2. Name the physical mechanisms of the soil that operate in land application systems.

3. Describe the chemical mechanisms that operate in land application systems.

4. Explain the biological mechanisms that operate in land application systems including the three general stages of decomposition of newly added organic material.

5. Summarize the limitations on the waste treatment system that are imposed by adding nitrogen, organics, sodium, phosphorus, and potentially toxic materials such as zinc and cadmium to the site.

Introduction

Soil, as a physical, chemical, and biological complex, is a highly variable medium. In the absence of clearcut rules to follow for waste application, predictive judgments must be made on a site-specific basis after thorough evaluation of individual soil properties and their variability.

Land application systems are commonly classified in terms of water transmission properties of soil. Soils with high transmission capabilities are considered suitable for "rapid infiltration" systems; soils with moderate transmission rates are suited for use with conventional "irrigation" methods; gently sloping soils with low transmission capabilities are normally suitable only for "overland flow" systems. Clearly, the behavior of water is an important consideration. Equally important is the potential for removal or alteration of other waste constituents including organics, pathogens, potentially toxic elements, dissolved salts, and major plant nutrients such as nitrogen and phosphorus. Site evaluation necessitates a basic understanding of soil components and properties, the treatment mechanisms operating in the soil, and limitations of these mechanisms in terms of pollutant loading rates.

Land application systems are generally related to the water transmission of the soil. Rapid infiltration for high transmission, irrigation for moderate transmission and overland flow for low transmission.

In common usage, the term "soil" conveys a variety of meanings to different people and therefore requires some clarification at the outset.

Figure 1 depicts a vertical section or profile of a landscape extending from the surface down to bedrock. All of the material above bedrock is technically termed the regolith. This unconsolidated mantle results from weathering of the underlying rock and/or deposition of material transported by gravity, wind, water, or ice. Living organisms and climatic factors combine to alter the upper portion of the regolith, giving rise to more or less distinct horizontal layers termed horizons. To a soil scientist, soil is only

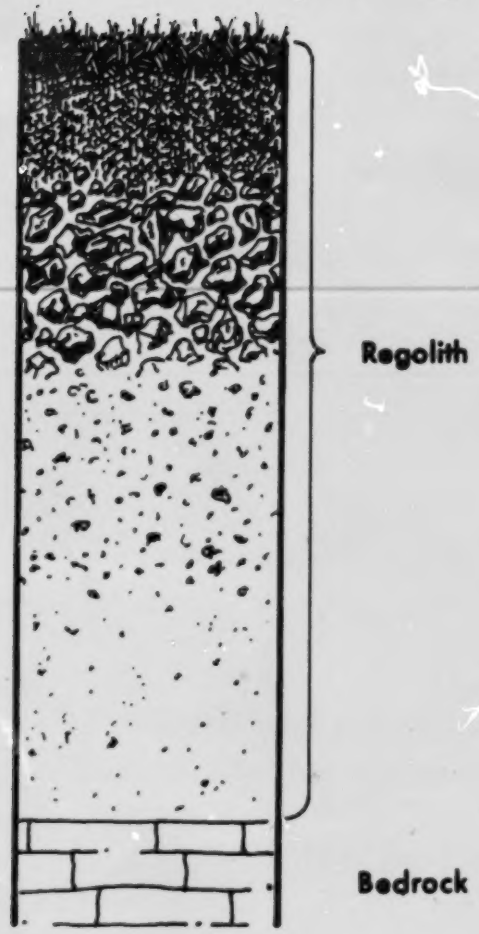


FIGURE 1. A vertical section of a landscape showing the unconsolidated mantle (regolith) overlying bedrock. Note the presence of more or less distinct horizontal layers in the upper portion of the regolith.

this most intensely altered zone within which the nature and sequence of horizons form a basis for differentiating and mapping individual soils. In this sense, soil seldom extends deeper than three to four feet in temperate latitudes, although the regolith may extend hundreds of feet.

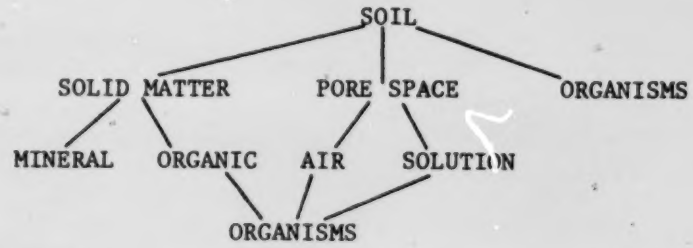
For purposes of waste treatment, however, it is convenient to use the term soil in a broader sense to include the entire regolith since much or all of the unconsolidated material can be instrumental in waste treatment. This broad interpretation of soil will be used in subsequent sections.

All material above bedrock is called the regolith; the term "soil" includes the entire regolith when speaking about waste treatment.

Properties of Soil Must be Examined

Soil consists of a solid matrix interspersed with pore spaces. The solid matter consists of both mineral particles derived from rock fragments and organic matter or humus resulting from the decay of plant and animal tissue. Pore spaces are filled either with air or with a solution of water and dissolved salts. In combination, these constituents provide an environment for a host of living organisms.

Soil consists of a solid matrix interspersed with pore spaces.



The behavior of water and other waste constituents in soil is closely related to the size and arrangement of the mineral particles and the amount of organic matter, which in turn determine the nature and amount of pore space. Figure 2 shows the approximate proportions of soil components in the surface or plow layer (6-8 inches) of a representative agricultural soil. Solid matter and pore space occupy about equal volumes. Organic matter comprises from 1-10% of the solid fraction with the remainder being mineral particles. Pore space is about evenly divided between air and solution unless the soil is very wet or very dry.

The behavior of wastewater in soil is influenced by the nature of the pore spaces, in turn determined by the characteristics of mineral particles and organic matter.

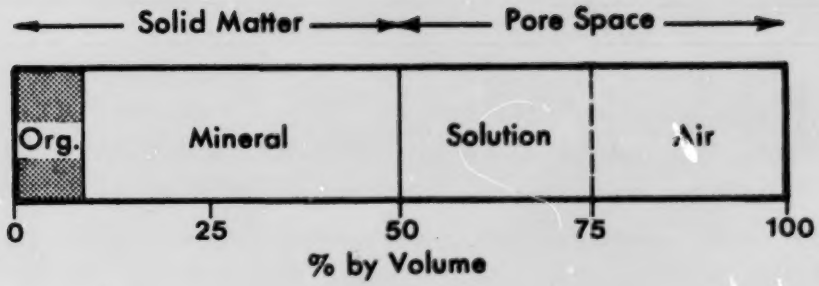


FIGURE 2. Volume composition of an agricultural surface soil (6 - 8 inches in depth) representing favorable conditions for plant growth.

It must be stressed, however, that soil is highly variable both in space and time. For example, the amount of organic matter changes markedly with depth as does the size and arrangement of mineral particles. Likewise, the relative proportions of air and solution fluctuate widely in accordance with climatic events and land use. In order to evaluate soil as a medium for waste application and treatment, it is therefore necessary to further characterize soil variability.

Figure 3 depicts three different soil profiles, each to a depth of four feet. These profiles, from top to bottom, exhibit properties generally suitable for "rapid infiltration," "irrigation," and "overland flow" systems, respectively. Specific properties of interest in waste application are illustrated in subsequent figures. The vertical axis in each case indicates depth while the horizontal scale is per cent by volume to show relative amounts of soil components. The alternately banded scale to the right of each profile delineates horizons of textural classes and structural differentiations within the soil profile. This and other information will be added in subsequent figures which will follow the same basic format of Figure 3. The heavy black line separates solid matter from pore space; within the solid fraction, the darkened area represents organic matter. Further distinctions of importance in waste application are made in the figures which follow on the basis of texture, structure, permeability, available water capacity, and cation exchange capacity.

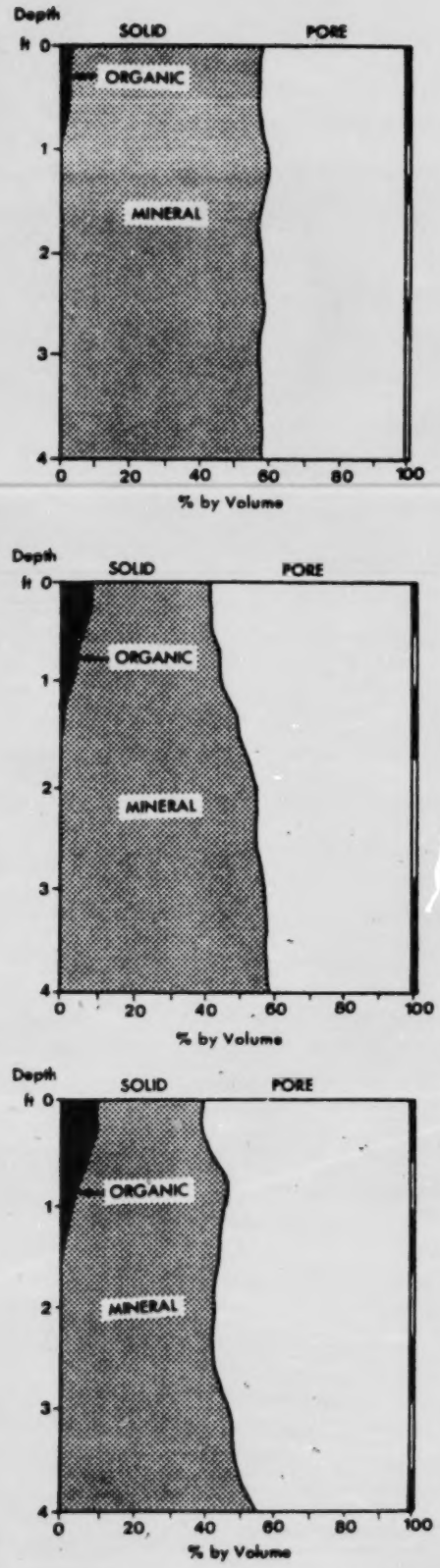


FIGURE 3. Profile diagrams for three soils with varying proportions of individual components. These soils, from top to bottom, represent conditions generally suitable for "rapid infiltration", "conventional irrigation", and "overland flow" wastewater application systems, respectively.

Soil Texture Describes Mineral Particles

Soil texture refers to the coarseness or fineness of the individual mineral particles. Various systems are used to categorize mineral particle size: three systems are shown in Figure 4. Within the USDA scheme, which will be used in this module, soils are given textural class nam s based on the relative amounts of sand, silt, and clay in the surface layer. These basic textural classes are listed in Table 1 along with alternate terms commonly encountered in soil descriptions. By definition, sandy soils are those in which sand makes up 70% or more of the material by weight. A clayey soil must contain at least 35% clay. Between these extremes, loamy soils contain variable mixtures of sand, silt, and clay.

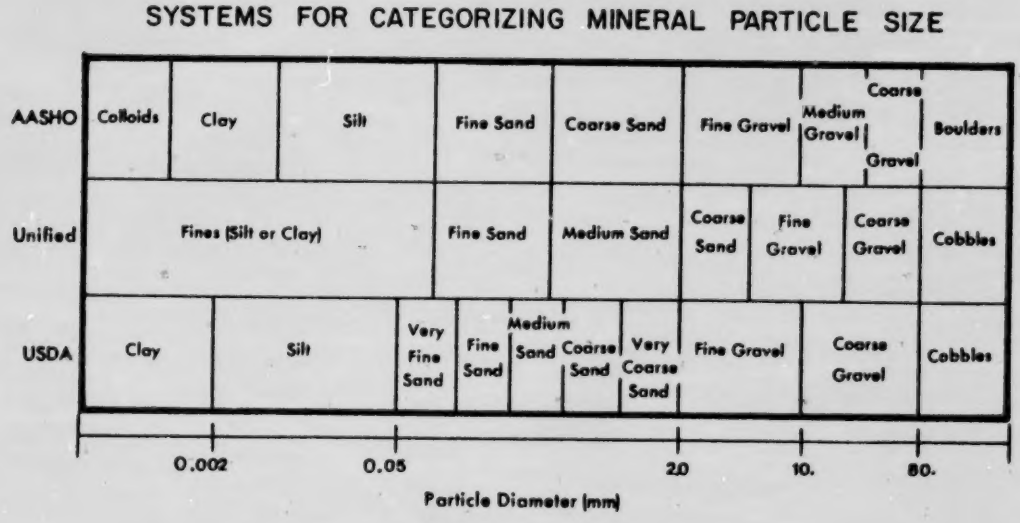


FIGURE 4. Three common systems for categorizing mineral particle sizes in soil according to the American Association of State Highway Officials (AASHO), the U.S. Army Corps of Engineers (Unified), and the U.S. Department of Agriculture (USDA).

Table 1

Soil Textural Classes and General Terminology
Used in Soil Descriptions
(After Soil Survey Staff, 1951)

General Terms		Basic Soil Textural Class Names
Common Names	Texture	
Sandy Soils	Coarse	Sandy Loamy sand
Loamy Soils	Moderately Coarse	Sandy loam Fine sandy loam
	Medium	Very fine sandy loam Loam Silt loam Silt
	Moderately Fine	Clay loam Sandy clay loam Silty clay loam
Clayey Soils	Fine	Sandy clay Silty clay Clay

Textural characteristics for the three soil profiles previously introduced are shown in Figure 5. Note that the textural class name assigned on the basis of surface texture does not necessarily reflect conditions deeper in the profile. Textural variability along with structure is particularly important in determining water transmission rates.

Soils are given a textural class according to the relative amounts of sand, silt, and clay in the surface layer.

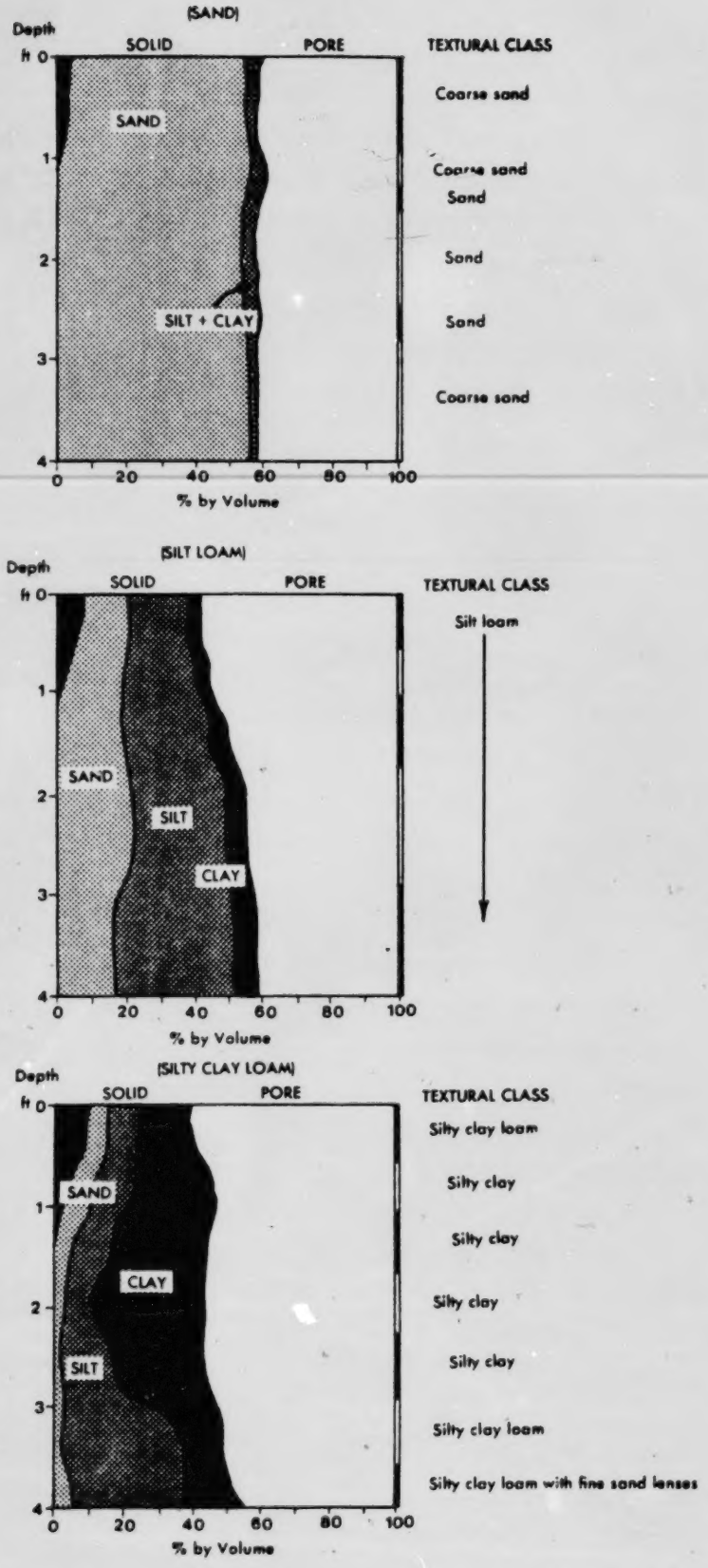


FIGURE 5. Soil profile diagrams showing textural variability.

Soil Structure Describes Organization of Individual Particles

Soil structure refers to the organization of individual particles into clumps or aggregates. Sandy soils tend to be relatively structureless, particularly below the surface layer. As the per cent of silt and clay increases, however, particle aggregation occurs, forming units that range from weak to stable, small to large, and simple to complex. The formation of stable aggregates is strongly favored by increasing amounts of organic matter. Common structural types are illustrated in Figure 6.

Soil structure is determined by the degree of aggregation of individual particles.

A soil profile may be dominated by a single kind of structure although usually a number of different types are encountered with depth depending on texture and organic matter content. Figure 7 indicates the structural variability occurring in the three profile diagrams.

Note the occurrence of granular structure in the surface layers of all three profiles. Granular aggregates result from the presence of organic matter (humus). This kind of structure is highly desirable, particularly in loamy and clayey soils where it improves the air and water transmission capabilities. Granular structure, more than any other type, can be maintained or destroyed by management practices. Blocky and prismatic aggregates generally occur well below the surface and are less affected by management practices. However, both of these structural units are affected by moisture. Depending on the type of clay present, the aggregates may swell upon wetting, forming a tight and nearly impermeable mass. On the other hand, upon drying, shrinkage cracks between the individual aggregates may allow rapid downward movement of water.

Granular aggregates, which are desirable for waste treatment sites, result from the presence of organic matter. Granular structure can be maintained or destroyed by management of the site.

STRUCTURAL TYPE	OCCURRENCE	GENERAL INFLUENCE ON WATER TRANSMISSION
Granular	Surface Horizons	Encourages
Blocky	Sub-surface Horizons	Restricts
Prismatic	Sub-surface Horizons	Restricts
Platy	Surface or Sub-surface Horizons	Severely Restricts

FIGURE 6. Common soil structural types vary in appearance, occurrence, and in their effect on water transmission through the soil (adapted from Donahue et al. 1971).

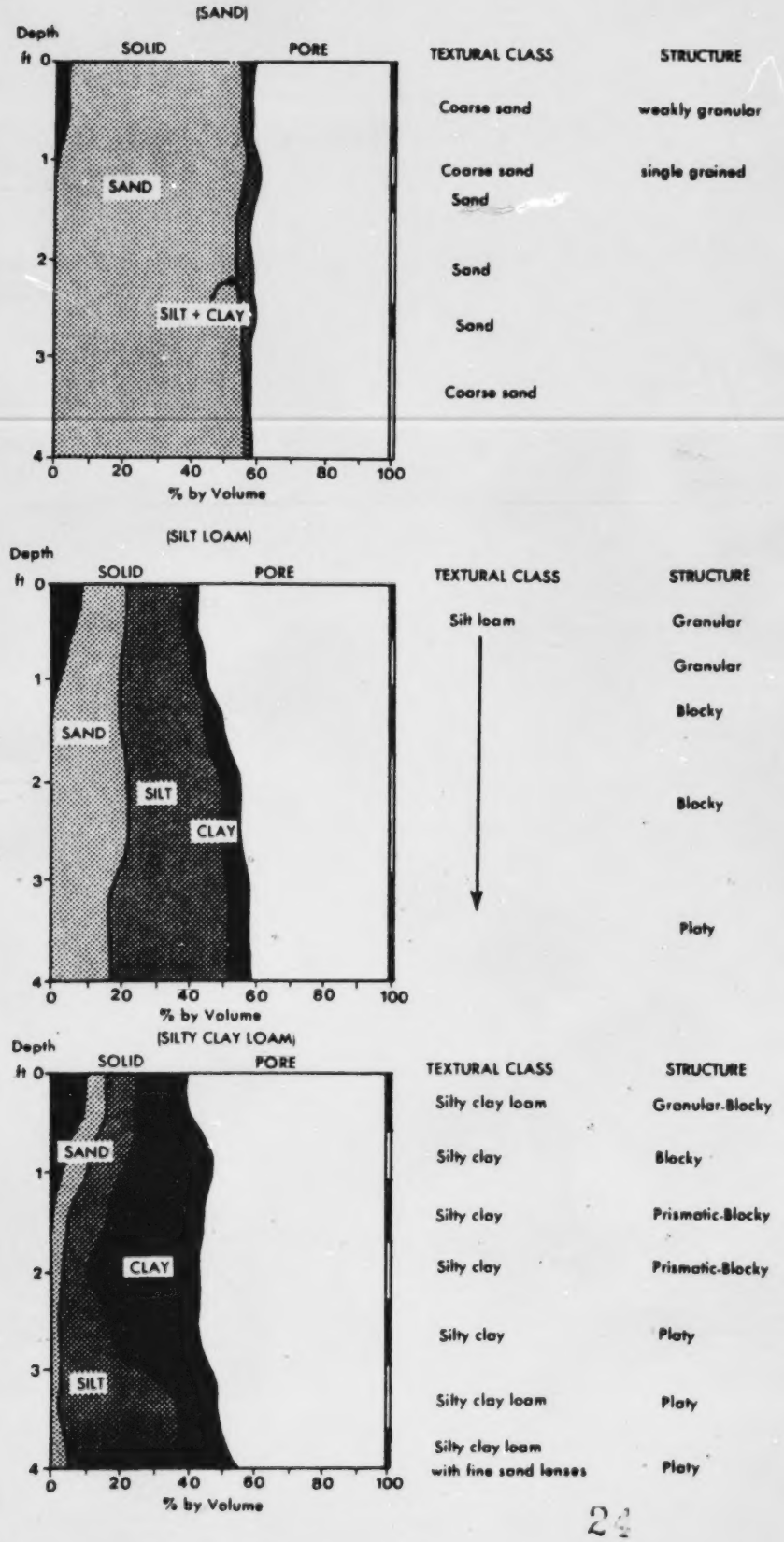


FIGURE 7. Soil profile diagrams indicating structural variability.

Permeability Describes Transmission of Air, Water Through Soil

Permeability, a property determined by soil pore space, refers to the ease with which water and air are transmitted through the soil. Conditions which favor the transmission of water, however, will generally also favor the movement of air unless the soil is saturated (all pores filled with water). In this section we will therefore concentrate on permeability to water.

Permeability may be quantified in terms of the rate of water movement through a unit cross section of saturated soil in unit time and is commonly expressed in inches/hour. The cooperative Soil Survey of the Soil Conservation Service has defined permeability classes for use in describing and interpreting soils. These classes are listed in Table 2.

The size of the pores in the soil determines permeability, the ease with which water and air are transmitted through the soil.

Table 2

Permeability Classes for Saturated Soil

Soil Permeability (inch/hr)	Class
Less than 0.06	very slow
0.06 to 0.2	slow
0.2 to 0.6	moderately slow
0.6 to 2.0	moderate
2.0 to 6.0	moderately rapid
6.0 to 20	rapid
More than 20	very rapid

SOURCE: USDA, Soil Conservation Service, 1971.

Although exceptions do exist, fine textured soils generally possess slow or very slow permeability while values for coarse textured soils range from moderately rapid to very rapid. A medium textured soil such as a loam or silt loam tends to have moderate to moderately slow permeability. Referring to Figure 7, however, we can see that the coarse sand has the least total pore space while the finer textured silty clay loam shows the greatest. The reason for this seeming paradox is that permeability is more a function of pore size than total pore space.

The finer the texture of the soil the slower the permeability tends to be. Coarse textured soils have moderately rapid to very rapid permeability.

Individual pores vary in size from a few microns to several millimeters in diameter. For convenience, pores are often simply divided into macropores, and micro- or capillary pores. Macropores, by definition, transmit water readily in saturated soils in response to gravity. In contrast, micropores retain water against gravitational force.

In saturated soil, macropores transmit water readily in response to gravity; micropores retain water against gravity.

In Figure 8, the macropore-micropore distinction has been indicated on each of the three profiles along with permeability estimates. The coarse sand showing the least total pore space is dominated by macropores and thus shows the highest overall permeability. Conversely, the silty clay loam, with the highest total pore space, has the least amount of macropores and thus the lowest overall permeability. Note the variability in macropore space with depth. Macropore space and thus permeability are clearly related to the texture and structure of individual soil layers.

A high proportion of macropores speeds permeability; a high proportion of micropores slows permeability.

Infiltration Describes Water's Rate of Entry Into Soil

Closely related to permeability is infiltration rate, defined as the rate at which water enters the soil surface. Infiltration rate, expressed in inches/hour, is influenced by both permeability and the moisture content of the soil. In an initially dry soil with much of the pore space filled with air, applied water enters the soil, displacing air and gradually filling the pore space. The infiltration rate, however, decreases with continued application, approaching a constant. At saturation, the constant equals the permeability of the least permeable horizon of soil layer in the profile. Continued application in excess of the limiting rate will result in surface ponding and runoff. An exception often occurs on slopes where excess water may move laterally along the face of the least permeable layer. In such cases, water will likely emerge at the slope base some distance from the original point of application. Infiltration rate thus depends on permeability within the profile, and on topography.

Infiltration rate depends on permeability, moisture content of the soil, and topography.

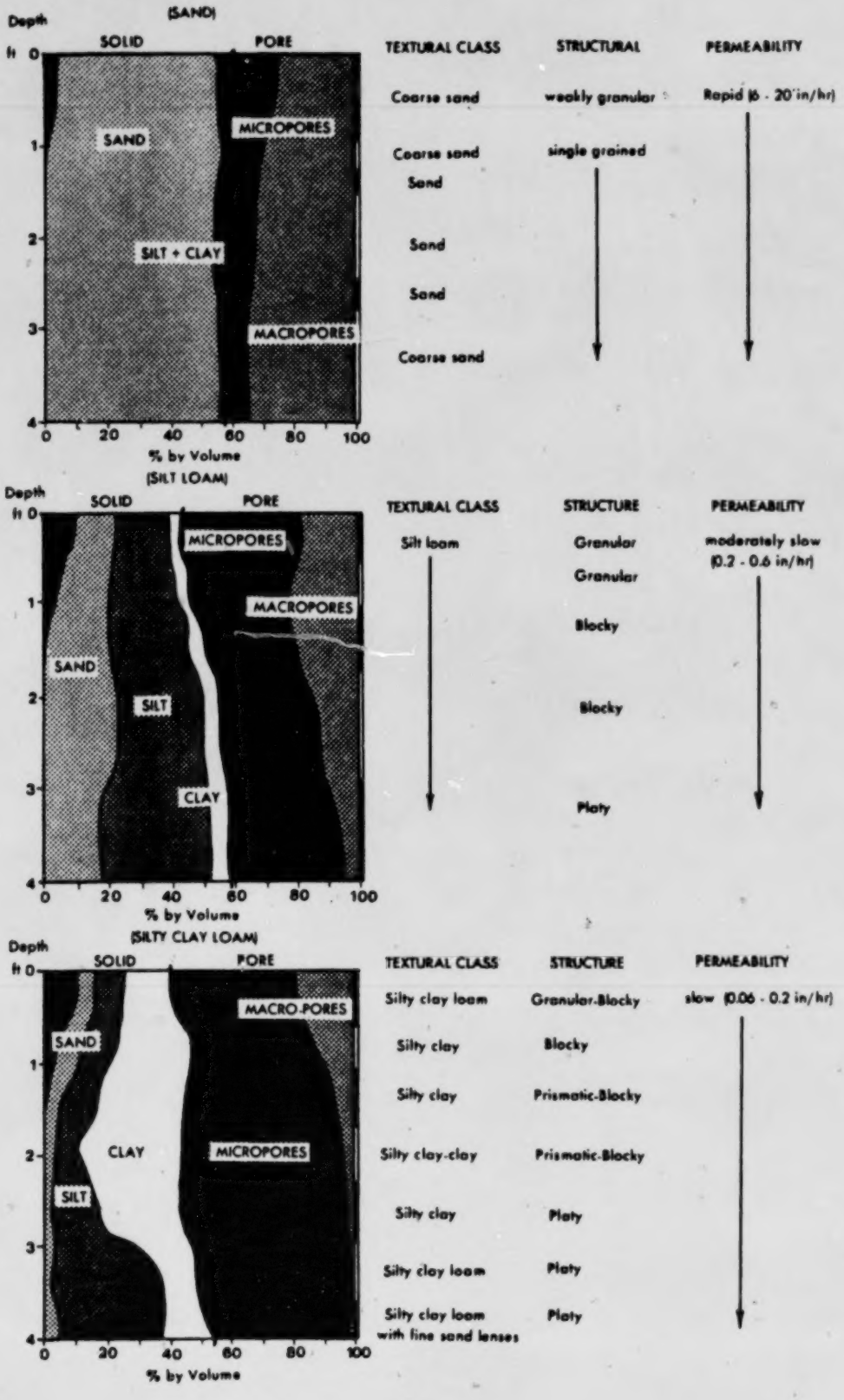


FIGURE 8. Soil profile diagrams depicting variability in the proportion of macropore and micropore space and overall permeability.

Available Water Capacity Affects Behavior of Applied Wastewater

Yet another property of the soil pore space, the available water capacity, affects the behavior of applied wastewater. To illustrate this property, consider a soil that is completely saturated. If no further rainfall or wastewater addition occurs, the macropore space will drain in response to gravity within approximately 48 hours. The micropores, however, will remain essentially filled with water. The moisture content of the soil at this point is referred to as field capacity. A portion of this moisture is extractable by plant roots while another portion is held too tightly for plant use. The dividing point between these two entities is termed the permanent wilting point. Available water capacity (AWC), expressed as inches of water per some unit of depth, is defined as that amount of water which is held in the soil between field capacity and the permanent wilting point.

Available water capacity varies with the amount of micropore space which in turn depends on texture, structure, and organic matter (Figure 9). The coarse sand has the smallest AWC; most of the micropore space and thus most of the available water in the profile is in the surface layer due to the organic matter content there. The silt loam profile, with a much greater micropore space, has a much higher AWC. However, a further increase in micropore space in the silty clay loam produces little increase in AWC. This is due to a concommitant increase in the amount of unavailable water. A still finer textured soil, for example a clay, might even show a decrease in available water. Figure 10 shows the general relationship between micropore space and AWC over a wide textural range.

Available water capacity (AWC) refers to the micropore water which plant roots can extract from the soil.

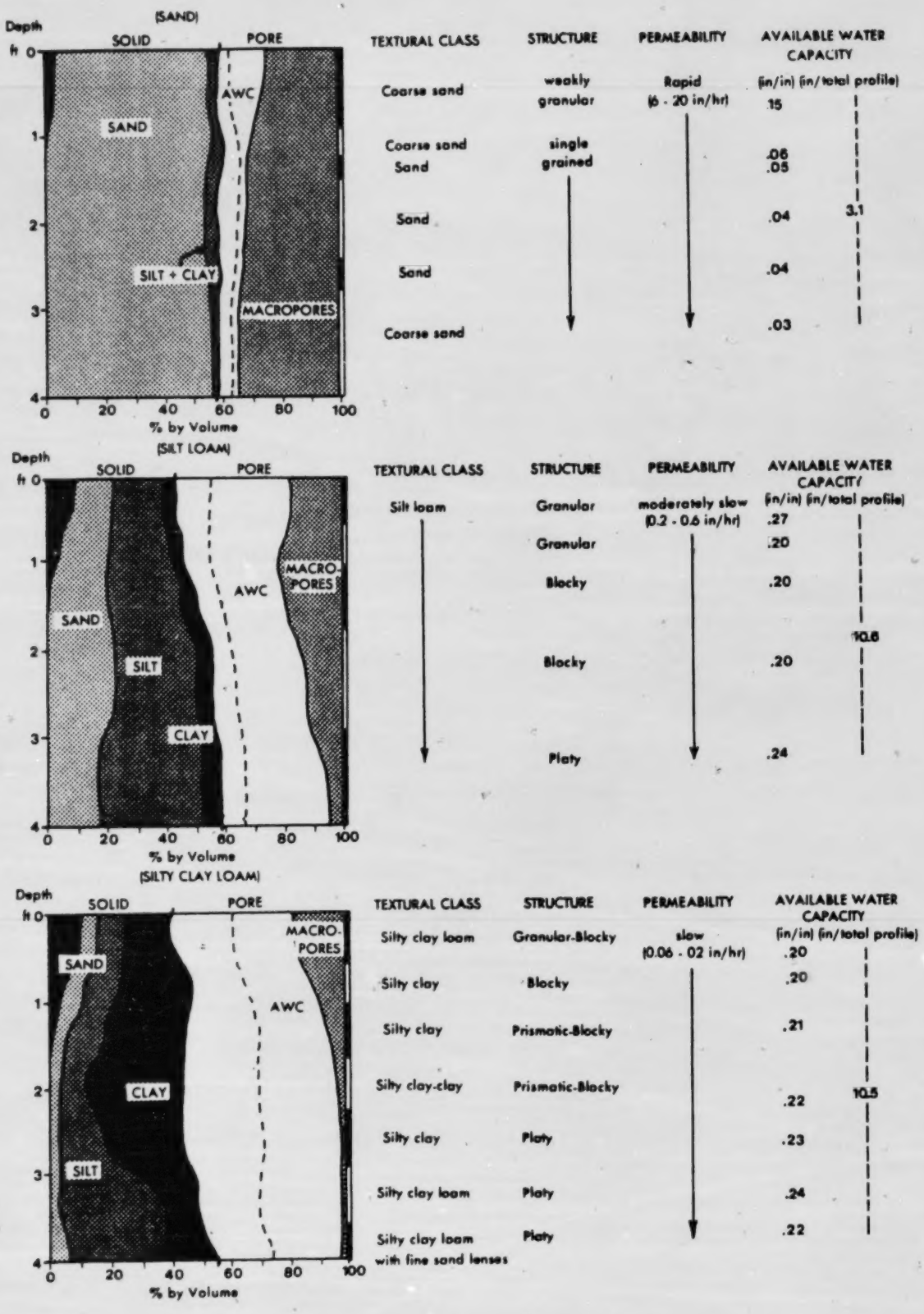


FIGURE 9. Soil profile diagrams showing variability in the available water capacity (AWC).

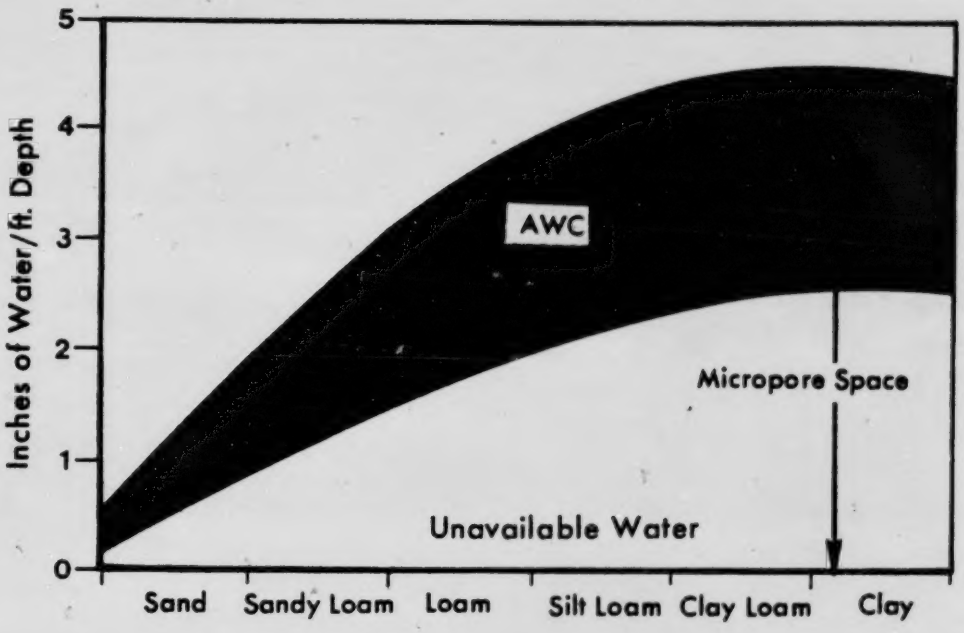


FIGURE 10. General relationship between micropore space, available water capacity, and textural class (adapted from Brady 1974).

The amount of available moisture in a soil has an obvious importance for plant growth, but is also important in the performance of wastewater application systems. The reaction and thus "treatment" of many waste constituents in the water depends on residence time in the soil. Since the available water capacity essentially measures the water storage capability of a soil, it reflects the amount of wastewater that can be applied to a dry soil without moving directly to the groundwater. Absorption of water by plants continuously depletes this store of available water during the growing season, and so allows for the retention of subsequent additions, whether wastewater or natural rainfall. The amount of depletion varies with climate and the type of vegetation. Vegetation aspects are discussed more fully in Module 7, "Vegetative Cover"; climatic factors are discussed in Module 8, "Climate and Wastewater Storage" and Module 2, "Site Evaluation".

Available Water Capacity of soil is essentially, its water storage capability. A high AWC increases residence time of waste constituents in soil, thus promoting treatment of wastes.

Cation Exchange Capacity Indicates Capacity for Reactions Between Charged Pollutants and Soil Particles

Up to this point our principle concern has been those properties of soil which determine water transmission and retention. Moving with the water, however, are other waste constituents, particularly dissolved ions and compounds. Somewhat like water these constituents are alternately retained and transmitted through the soil. The clay and humus fractions of soil are primarily responsible for their retention. Both clay and humus exist in the colloidal state, characterized by an extremely small size ($\leq$ 0.002 mm) and the presence of an electrical charge. The significance of the charge is that oppositely charged ions or compounds are attracted and held on the colloidal surfaces. The small size vastly increases the surface area available for such interaction. For example, a coarse sand has a surface area of perhaps 10-50 cm^2/g; in contrast, a clayey soil may exhibit a surface area in excess of 10,000 cm^2/g (Cassel and Vasey, 1974).

Wastes in the form of dissolved ions and compounds are retained and transmitted through soil depending on the Cation Exchange Capacity (CEC).

The net charge on colloidal particles in most soils is overwhelmingly negative. Consequently, the ions attracted are positively charged (cations) such as ammonium, calcium, magnesium, potassium, and sodium. Cation exchange capacity (CEC) is a measure of the ability of a soil to retain cations. Indirectly, however, CEC serves as a rough index of all reactions which occur between charged pollutants and colloidal surfaces. In general, the greater the CEC of a particular soil, the greater the potential for effective waste treatment.

CEC is a rough index of all reactions between charged pollutants and extremely small, charged soil fractions called colloids.

Cation exchange capacity, expressed in milliequivalents per 100 grams of soil or colloid (meq/100 g) varies markedly with the organic matter content and the amount and type of clay present. For a sample of pure humus, CEC averages about 200 meq/100 g, whereas for vermiculite, montmorillonite, chlorite, kaolinite, and hydrous oxide clays, average values are 150, 100, 30, 8, and 4 meq/100 g, respectively (Brady, 1974).

Because of its dependence on clay and humus content, CEC can be expected to vary both within and among soil profiles. Figure 11 indicates CEC variation in each of the three profiles. Considering all of the properties discussed thus far, we can see that soils with the highest water transmission capabilities have the lowest potential for effective waste treatment as indicated by CEC. In contrast, soils most likely to remove waste constituents can accept but limited hydraulic loads. Thus "rapid infiltration" systems generally require some sacrifice, often large, in chemical removal or treatment potential. "Overland flow" systems, although usually involving soils with high CEC values, cannot make full use of this treatment potential due to limited contact with the soil mass below the immediate surface. "Irrigation" systems are intermediate with perhaps the optimum mix of water transmission and waste treatment properties. Soils with moderate to high treatment potential offer the possibility of installing artificial drainage systems (e.g., underground tile lines) to improve water transmission.

Soils with a high CEC have a high potential for effective waste treatment because more reactions occur between soil and waste constituents.

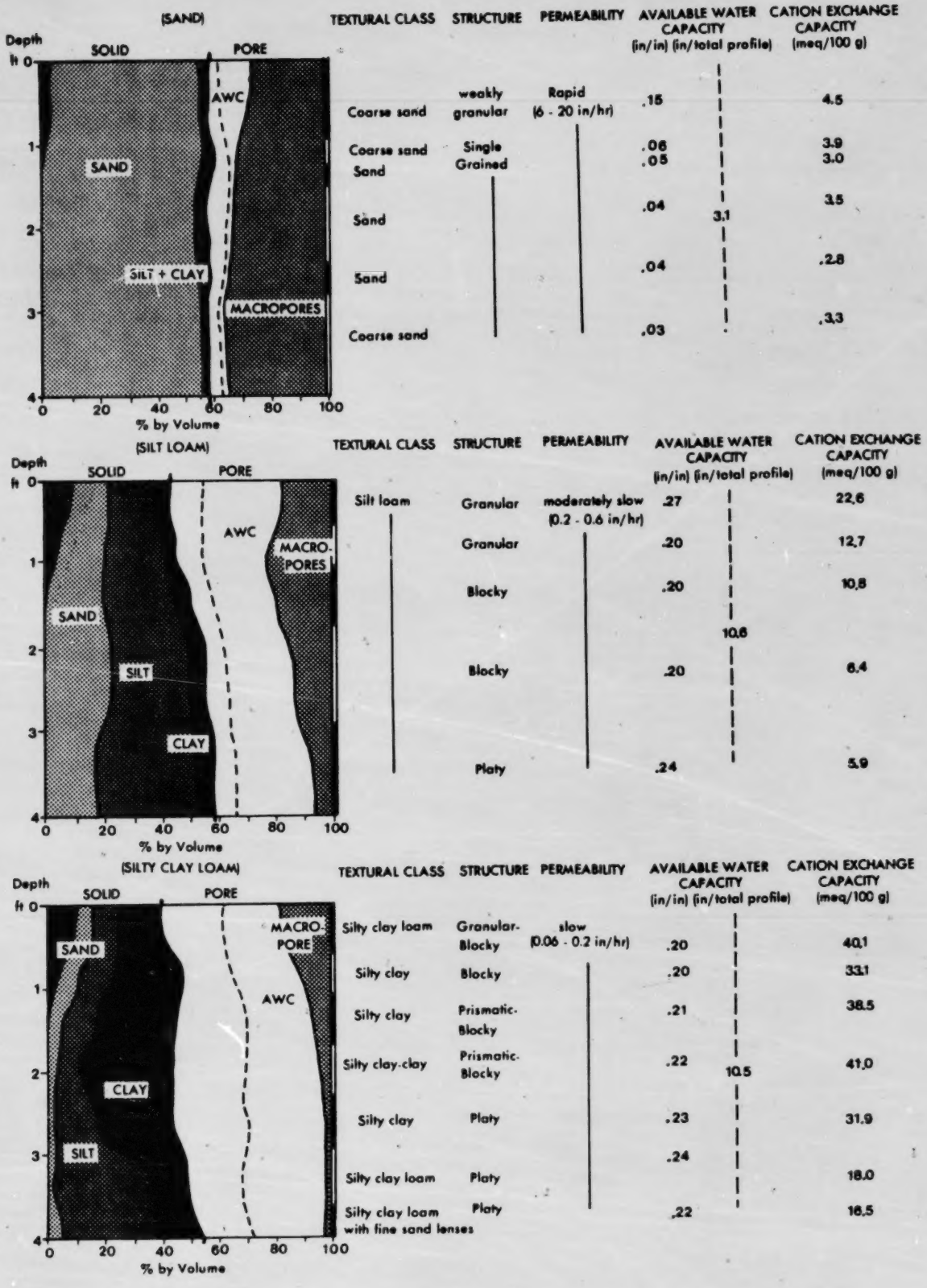


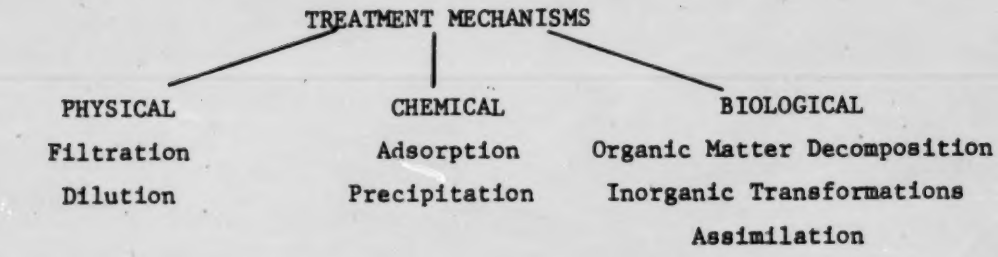
FIGURE 11. Soil profile diagrams indicating variability in cation exchange capacity (CEC).

Treatment Mechanisms and Loading Limitations Control Pollutants

The use of the soil as a treatment medium may be a new concept to some since historical usage has stressed land application for waste "disposal". Nothing, however, is actually disposed of. Instead, some materials pass through the soil and into the groundwater, some are utilized by growing plants, while others are retained almost indefinitely within the soil. Proper design of land application facilities must relate the fate of pollutants to the properties of soil with which they may interact and minimize the fraction of contaminants passing through to groundwater. Those people with experience in the design of wastewater treatment systems have a broad knowledge of processes which have been developed to control specific pollutants. There are several separate unit processes that can be adopted for removal of SS, TDS, BOD_5, N, P, or potentially toxic elements and an almost unlimited combination of these which ultimately comprise the treatment system. For the common processes, the design engineer can quickly relate the quantity of a pollutant to the capacity of the process, the rate of reaction, the quantities of materials involved, and the efficiencies. An attempt has been made to summarize some of this material in Module 5, "Waste Characteristics" and Module 4, "Treatment Systems, Effluent Qualities and Costs". Many of the same pollutant control mechanisms are operative in soils, but few people can put them into context with conventional processes.

Wastes are not "disposed of" in land treatment, but rather they are utilized by plants, retained in the soil, or pass through the soil to the groundwater.

Waste treatment mechanisms that occur in soils can conveniently be categorized as physical, chemical, and biological. Within each category, various processes act to remove or alter specific waste constituents.



Filtration Acts as Physical Treatment Mechanism; Dilution Alters Waste Concentrations

As wastewater moves into and through soil pores, suspended solids are removed by mechanical filtration. The actual depth at which removal occurs varies with the size of suspended particles, soil texture, and the rate of application. The larger the hydraulic loading rate and the coarser the soil, the greater the distance required. However, when loading rates are such that much of the applied water is held in the soil, additional removal can occur as suspended materials settle out or adhere to the surfaces of soil particles.

The larger the hydraulic loading rate and the coarser the soil, the greater distance is required to filter out suspended solids from waste.

Some organic particles and certain organisms such as worms and protozoa are large enough so that removal by simple blockage is likely. Both bacteria and viruses, however, are small enough so that based on size alone, movement through the pores of many soils could be expected (Burge, 1974). Nevertheless, in the limited studies reported to date, it appears that most wastewater pathogens are removed in the upper few feet of all but the very coarse textured soils. Filtration by the soil and, in some cases, by an additional organic mat formed in the top 0.2 inches of soil is the primary means of retaining bacteria in the soil (Metcalf and Eddy, 1977). Adsorption to soil particles is the basic virus retention mechanism. Module 9, "Pathogens" contains further discussion on this subject.

Applied wastewater may also be diluted either upon entering the groundwater or by augmentation in the soil with natural rainfall or snowmelt. The dilution process is furthered by chemical and biological removal of dissolved waste constituents. The reverse of dilution--concentration--may also occur, particularly in arid or semi-arid climates where evaporation losses are high.

Filtration is the primary means of retaining bacteria in the soil, preventing them from moving to the groundwater. Virus removal is by adsorption.

Physical Mechanisms of Waste Removal are Limited

Suspended materials can, at times, clog soil pores and thereby severely reduce the infiltration rate. The possibility of such clogging may lead to strict requirements for pretreatment removal of suspended solids (SS). With the limited information available, however, it appears likely that other waste constituents such as nitrogen and toxic elements will limit waste applications in most cases before any significant negative effects of suspended solids are encountered.

Useful information on physical clogging of soils can be obtained from the results of sand filtration in conventional sewage treatment systems (Metcalf and Eddy, 1972). Sand filters effectively trap fine suspended solids from secondary effluents in the first few inches of filter depth. Loadings of SS may reach values equivalent to 62,500 lbs. SS/acre-day (at 6 gpm/ft^2 application of 20 mg/l SS). With such loading, however, there is generally a rapid decrease in hydraulic conductivity over a period of 24 hours or less. Application periods must then be followed by a backwash (reversing flow direction) to remove the clogging particles. In contrast, land application systems can recover from clogging through natural decomposition of the suspended solids during non-application or resting periods. Furthermore, common SS loadings to land are far less than those used in conventional sand filtration processes. Two inches of effluent per week applied to the land would add less than 5,000 lbs SS/acre-yr.

Clogging of suspended solids at land application sites is corrected through the natural decomposition of the solids during periods of non-application.

A closer approximation of a design SS loading can be obtained from studies of septic tank systems (McGauhey et al., 1966; Laak, 1970). A general rule of thumb is that the maximum continuous application rate for septic tank effluent on soil is about 5% of the percolation rate as measured with clean water. This may well be too conservative for systems which allow for drying and recovery. Figure 12 illustrates the recovery capability of a soil when allowed to rest in an aerobic state after successive periods of flooding with septic tank effluent. Data from Laak (1970) indicate that for a variety of soils, wastewater applications of up to 3 inches/day, that is, about 200 lbs. SS/acre-day, will not cause significant clogging. When resting periods of 2-5 days are allowed between applications, this value could probably be raised to about 600 lbs. SS/acre-day.

Excessive clogging of the land treatment site can be avoided by proper pretreatment of wastes and alternating application with rest periods.

From these data, it appears that application scheduling and relatively simple pretreatment such as screening or primary sedimentation should be adequate to avoid excessive clogging.

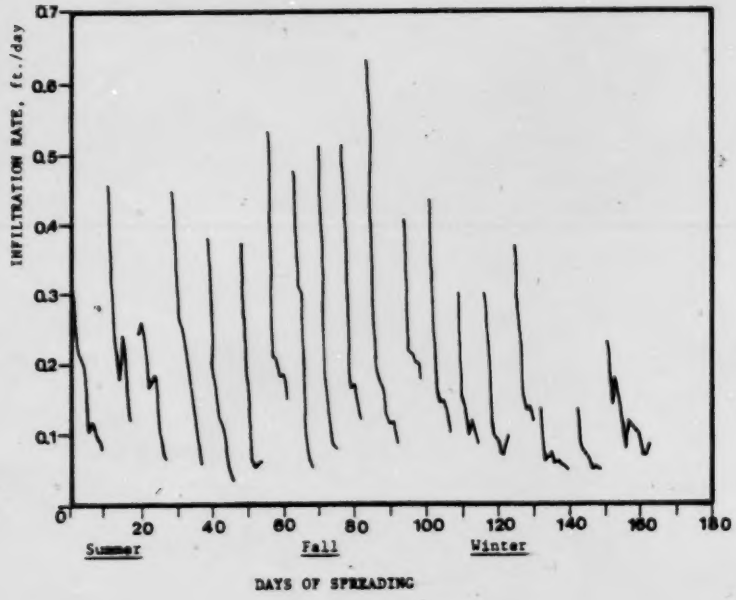


FIGURE 12. Recovery of infiltration rates in a Yolo loam soil after intermittent applications of primary sewage effluent (after McGauhey et al. 1966).

Wastes are Altered Through Adsorption and Precipitation

Chemical reactions among dissolved ions or compounds, and interactions with the soil solid phase alter the mobility of waste constituents. Some dissolved constituents are retained within the profile indefinitely while the movement of others is only temporarily restricted or unaffected.

Two chemical processes, adsorption and precipitation, account for most of the retention. Adsorption, as a loosely applied term, refers to the net effect of interactions between dissolved ions or compounds and the surfaces of clay and humus particles. In contrast, precipitation is the formation of an insoluble or slowly soluble product from constituents that were originally in solution.

Dissolved ions or compounds in wastewater are retained in soil primarily through adsorption and chemical precipitation.

Ion exchange is one type of adsorption process. A distinction is made between anion exchange (involving negatively charged ions or compounds) and cation exchange (involving positively charged ions or compounds). Under acid conditions, that is pH less than 5, some soils have the ability to hold small amounts of anions such as nitrate, sulfate, and phosphate in an exchangeable form. The hydrous oxide clays of iron and aluminum are most responsible for anion exchange properties. Anion exchange, however, is of very minor importance in land application systems. Phosphorus is the only anion appreciably retained in soils, though the primary mechanism is not anion exchange.

The predominant ion exchange reactions in most U.S. soils involve cations. The magnitude of cation exchange properties in soil is measurable by the cation exchange capacity (CEC), a term introduced in a previous section. Cation exchange is a function of both the relative intensity of attraction between ions and colloidal solids, and of the relative concentration of exchangeable ions present in the soil solution.

Ion exchange reactions in most U.S. soils involve cations, positively charged ions or compounds.

The following series shows various cations in decreasing order of intensity of attraction between the ion and soil colloids:

Al^{+3} > H^{+1} > Ca^{+2} > Mg^{+2} > K^{+1} > NH_4^{+1} > Na^{+1}

(Aluminum) (Hydrogen) (Calcium) (Magnesium) (Potassium) (Ammonium) (Sodium)

As an illustration, consider a closed system consisting of a solid colloidal phase and a solution phase (Figure 13a). Within the system assume equivalent amounts of calcium and sodium, distributed between the two phases. At any given instant, some cations are released into solution from the solid phase and others move into replace them. The system is said to be in dynamic equilibrium when these random exchanges occur without altering the overall proportion of the two cations in solution or on the solid phase. Because of the greater intensity of attraction between calcium and the colloidal surfaces, Ca^{+2} will dominate the charge sites at equilibrium.

Assume now that there is an influx of sodium into the system (Figure 13b). Due to the much greater concentration of Na^{+1} in solution, random exchanges in the solid phase now favor the replacement of Ca^{+2}, despite its greater intensity of attraction. Therefore, at equilibrium, Na^{+1} will likely occupy the greater number of charge sites. Similarly, in wastewater treatment systems, the retention of dissolved cations depends largely on their concentration in the solution entering the soil.

The reaction in which sodium replaces some other cation is particularly important. A dominance of sodium on the soil colloids weakens the stability of soil aggregates causing dispersion and swelling. This in turn decreases the macropore space and thus sharply reduces permeability.

Exchange reactions involving ammonium (NH_4^{+1}) are also of special interest, since they offer one means to retain nitrogen at least temporarily. Such retention allows time for biological processes to transform ammonium to nitrate, (NO_3^{-1}), a highly mobile anion.

In wastewater treatment systems the retention of dissolved cations depends largely on their concentration in the solution entering the soil. Large concentrations will overcome a higher degree of attraction of other cations toward the soil matrix.

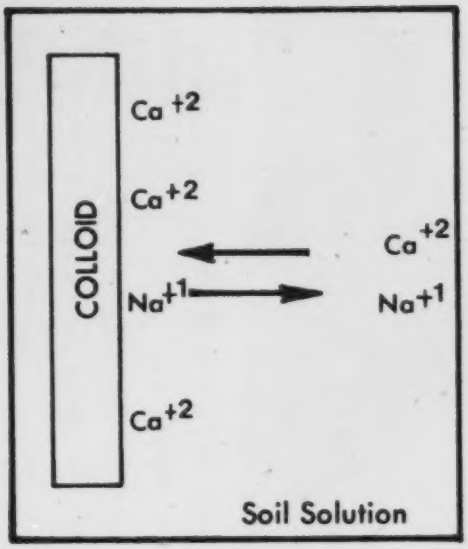


FIGURE 13a. The intensity of attraction between soil colloids and specific cations influences the cation exchange process; Ca^{+2} is more strongly attracted and thus dominates the colloidal charge sites.

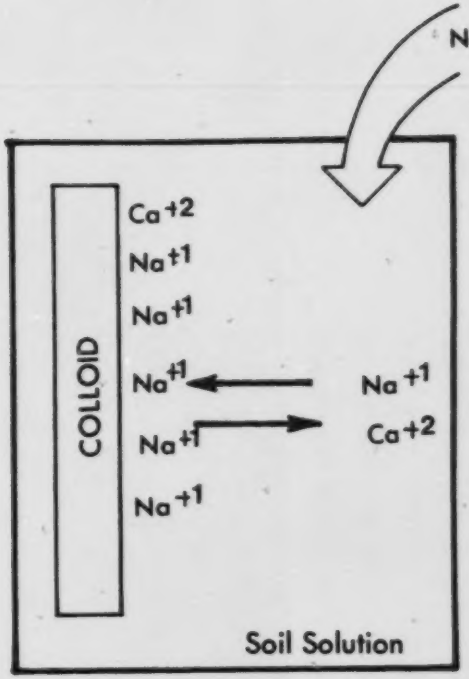


FIGURE 13b. Concentration can offset the effect of intensity of attraction; although Ca^{+2} is more strongly attracted, the greater concentration of Na^{+1} enables it to dominate the colloidal charge sites.

It must be emphasized that by definition exchangeable cations are replaceable. Thus, when sodium, ammonium, or any other cation is removed from wastewater via cation exchange, there must be a simultaneous release of some other cations into solution. The net effect is therefore some readjustment in the composition of the exchanger and solution phases, but the total soluble salt concentration does not change appreciably.

Exchangeable cations are replaceable and when any cation is removed from wastewater via cation exchange, there must be a simultaneous release of some other cations into solution.

Soils have a variable capacity to retain certain cations and anions so tightly that they are not exchangeable, a process termed specific adsorption. Like ion exchange, specific adsorption occurs between ions or compounds in solution and the solid colloidal phase. For example, orthophosphate anions ($H_2PO_4^{-1}$, HPO_4^{-2}) react on the surfaces of iron- and aluminum-containing clays. Initially, this phosphate may be exchangeable with other anions but with time it becomes more and more tightly bound. One explanation for this so-called reversion is that the phosphate becomes incorporated into the soil solid phase as an impurity (Brady, 1974).

Specific adsorption occurs when soils retain certain cations and anions so tightly that they are not exchangeable. Heavy metal cations such as zinc, copper, nickel, cadmium, and lead are incorporated into the soil in a non-exchangeable form.

Many of the heavy metal cations such as zinc, copper, nickel, cadmium, mercury, lead, and chromium are present in wastewaters at concentrations too low to be appreciably affected by cation exchange reactions. However, these cations seem to be incorporated into the soil solid phase in a non-exchangeable form. The actual reversion mechanisms remain poorly understood. CEC is the most important soil parameter for immobilizing the metal constituents in sludge. The concentrations of these ions is much higher in sludge than wastewater, which enables interaction with soil CEC to proceed more readily.

The effectiveness of soil in the removal of waste constituents either by ion exchange or specific adsorption is dependent upon contact between dissolved substances and the appropriate colloidal phases. Contact depends largely on the degree to which a soil is uniformly wetted. Initially, only the external surfaces of aggregates are in direct contact with wastewater. Over the longer term, internal surfaces tend to equilibrate with constituents held on external surfaces. Thus, the length of time that the water remains in the soil

The more uniformly the soil is wetted the more effective are ion exchange and specific adsorption mechanisms.

in no small way affects the amount of waste constituents that can be removed from the water. This consideration is important in determining application rates and also the frequency of rest periods. Over extended periods, the adsorption capability may be rejuvenated through reversion processes.

The chemical mechanisms discussed thus far have involved the interaction of dissolved constituents and the solid colloidal phase in the soil. Many ion species react within the solution phase itself, resulting in the formation of insoluble or slowly soluble precipitates. The point at which chemical precipitation occurs depends on the concentration of the participating ions as defined by their solubility product constant (K_{sp}). The solubility product constant is obtained by multiplying together the concentration of reactants (moles/l) in a saturated solution.

For example, the K_{sp} value for calcium sulfate ($CaSO_4$) is 2.4×10^{-5}. This means that whenever the concentration of the sulfate ion times the concentration of the calcium ion exceeds 2.4×10^{-5}, $CaSO_4$ will precipitate out of solution. Suppose the sulfate concentration in applied wastewater was 125 mg/l (1.3×10^{-3} moles/l). According to the solubility product, the concentration of calcium in solution cannot exceed 750 mg/l (1.85×10^{-2} moles/l). If, after entering the soil, evaporation caused the wastewater to become more concentrated, the product of Ca^{+2} and SO_4^{-2} would exceed the K_{sp} value and the reaction below would proceed to the right, forming insoluble $CaSO_4$.

Many types of ions react within the solution phase itself, forming insoluble slowly soluble precipitates.

$$Ca^{+2} + SO_4^{-2} \rightleftharpoons CaSO_4 \downarrow$$

The addition of rainwater and/or removal of reactants by ion exchange, specific adsorption or other means would tend to dilute the solution driving the above reaction to the left. Under such conditions, solid phase $CaSO_4$ dissolves.

In general, the concentrations of dissolved constituents in the soil solution cannot exceed the concentration defined by their solubility product constant. However, two notable exceptions exist. The first occurs in cases where the formation of a precipitate proceeds very slowly. For example, although varasite [$Al(H_2PO_4)(OH)_2$] is highly insoluble in soil ($K_{sp} = 3 \times 10^{-31}$), its formation may take weeks or even months. This reaction is one of many which account for the long-term retention of phosphorus in soils. The second exception is due to formation of organic complexes (chelates). As an example, certain soluble organic compounds can incorporate heavy metal cations into their structure. The cations thus remain in solution but are not subject to chemical precipitation reactions. In effect, the formation of complexes reduces the soil's ability to retain heavy metals through precipitation reactions.

The formation of organic complexes or chelates reduces the soil's ability to retain heavy metals through precipitation reactions.

Chemical Reactions are Limited in Removal of Waste Constituents

Two general types of waste constituents, potentially toxic elements and the macronutrients phosphorus and nitrogen, are at least partially controlled by chemical mechanisms in the soil. These are discussed in detail in Module 11, "Potentially Toxic Elements", Module 15, "Nitrogen Considerations" and Module 19, "Phosphorus Considerations". A brief description of soil capacities to "treat" these potential pollutants is presented here to enable approximation of soil loading limitations.

Potentially toxic elements, phosphorus and nitrogen are partially controlled by chemical mechanisms in soil.

Many of the toxic elements such as zinc (Zn), copper (Cu), and nickel (Ni) are positively charged and their retention in soil is related to the cation exchange capacity. Much research has been done in recent years with the intent of establishing application guidelines for heavy metals and other potentially toxic elements. Most attention has been focused on Zn, Cu, and Ni, which can be phytotoxic (toxic to plants) and Cd, which can accumulate in plants to levels toxic to animals consuming certain plant parts. Application levels have been proposed according to the relative

toxicity of the metals, soil texture, organic matter, and CEC. Environmental Protection Agency recommendations published in 1977 include the following guidelines (Table 3) for cumulative site lifetime loadings to private agricultural land, originally developed by the USDA. It is felt that cropland can accept these loadings, assuming good pH and other management control, with no restrictions on its productivity in the free market. The EPA recommendations suggest that higher application rates may be acceptable on publicly-owned land application sites employing adequate monitoring safeguards.

Table 3

Maximum Sludge Metal Applications for Privately Owned Farmland

		Soil CEC(meq/100g)		
	Metal	< 5	5-15	> 15
MAXIMUM METAL ADDITION (kg/hr)	Pb	500	1,000	2,000
	Zn	250	500	1,000
	Cu	125	250	500
	Ni	50	100	200
	Cd	5	10	20

Source: Dowdy, et al. (1976); Jorling (1977)

These guidelines, along with discussion of earlier work in metals application and the effects of specific elements on land application systems, are covered in full in Module 11, "Potentially Toxic Elements".

Several years ago, the focus on phosphorus removal from wastewater caused renewed interest in land application for this purpose. Agricultural experience had already shown that efficient phosphorus retention occurred in soils, but limitations of this removal capacity were not clear. Current knowledge indicates that phosphorus removal down to a concentration of 0.05 mg/l can be achieved over site lifetimes of 20 years or more at annual loading rates of at least 150 lbs. P/acre-yr., and perhaps twice this amount. Only the high-rate rapid infiltration systems exceed this rate of loading. However, efficient removal can only be achieved where intimate contact between wastewater and the soil is achieved. High efficiency P removal should therefore not be expected in overland flow systems.

Efficient removal of phosphorus can only be achieved where intimate contact between the soil and wastewater is achieved, making overland flow systems less effective even in good soil characteristics.

As will be seen throughout these modules, nitrogen loading constitutes a major limiting factor for most land application systems. For this reason, it is important that the reader understand the many aspects of the nitrogen cycle presented in Module 15, "Nitrogen Considerations". The chemical mechanism of most significance to nitrogen is the reaction of positively charged ammonium ions with the soil cation exchange complex. For a soil with a CEC of 15 meq/100 g, about 100 lbs. of ammonium-nitrogen per acre can be retained in this way before saturation is reached (Lance, 1972). In comparison, a two-inch application of unnitrified effluent would commonly add no more than about 16 lbs/acre of ammonium-nitrogen. Ammonium retention is a useful control mechanism on a short-term basis, but is of little long-term value since the ammonium ion is biologically converted to nitrate, a readily leached form of nitrogen.

Nitrogen loading is a major limiting factor in land application systems; the most important chemical mechanism for nitrogen removal is the reaction of positively charged ammonium ions with the soil cation exchange complex.

As noted earlier, the accumulation of sodium on the soil exchange complex can lead to a degradation of soil structure and thus a sharp reduction in infiltration and permeability rates. The sodium limitation of a wastewater is often expressed in terms of the sodium adsorption ratio (SAR). The SAR is defined as:

$$SAR = \frac{[Na^{+1}]}{\left(\frac{[Ca^{+2}] + [Mg^{+2}]}{2}\right)^{0.5}}$$

where the concentrations of sodium, calcium, and magnesium are expressed in milliequivalents per liter (meq/ℓ).

[NOTE] $\left(\frac{\text{mg } Na^{+1}/\ell}{22.99}\right) = \text{meq } Na^{+1}/1$; $\left(\frac{\text{mg } Ca^{+2}/\ell}{20.04}\right) = \text{meq } Ca^{+2}/\ell$;

$\left(\frac{\text{mg } Mg^{+2}/\ell}{12.15}\right) = \text{meq } Mg^{+2}/\ell$.

As a general rule, the SAR of applied wastewater should not exceed 10 (U.S. Salinity Laboratory Staff, 1953).

Biological Mechanisms Alter Waste Constituents in Stages

Organisms alter waste constituents through organic matter decomposition, inorganic transformations, and nutrient assimilation. Such biological "treatment" processes are largely restricted to the upper few feet of soil, sometimes termed the biologically active zone or rooting zone.

Biological treatment of wastewater occurs primarily in the upper few feet of soil called the rooting zone.

The ability of soil organisms to decompose organic compounds is a function of their population complexity. Soils normally contain a wide diversity of native organisms including many kinds of bacteria, fungi, actinomycetes, protozoa, worms, and insects along with higher plants and animals. Applies wastes usually contain additional types of organisms, especially bacteria, which may be few or absent in untreated soils. Decomposition of complex organics proceeds stepwise and involves many specific enzymes. Thus, the diversity of organisms enhances the capability of the soil to degrade a wide variety of organic substances.

The diversity of organisms in wastewater enhances the soil's ability to degrade a wide variety of organic substances.

Decomposition of newly added organic material may be envisioned as taking place in three general steps as shown in Figure 14. In general, this is the same sequence of reactions that takes place in a biological waste treatment plant. Initially, organisms digest the more easily decomposed material consuming oxygen and releasing carbon dioxide and water in the process. The five day biochemical oxygen demand (BOD_5) measures the amount of oxygen consumed in this stage. This pulse of activity is accompanied by a rapid increase in organism numbers. In cases of extreme organic overloading, temporary clogging of the soil can result.

The five day biochemical oxygen demand measures the amount of oxygen consumed initially by organisms digesting the more easily decomposed material.

In the second stage, organism numbers decline as the easily decomposed organic fraction is exhausted. The resulting mass of dead microbial tissue along with other intermediate decay products provide substrate for new and remaining organisms. This material, along with more resistant compounds from the original addition, the so-called refractory organics, are at least partially degraded to a relatively stable end product, humus.

In the second stage of biological treatment, dead microbial tissue from organisms die-off; intermediate decayed products and certain resistant compounds are partially degraded forming humus.

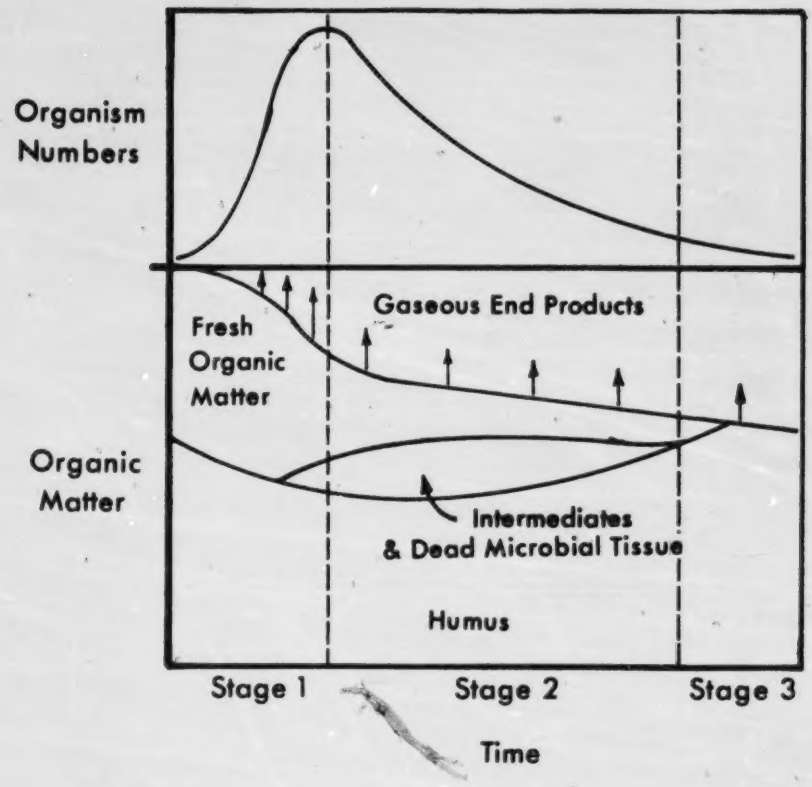


FIGURE 14. When fresh organic material is added to soil, decomposition occurs in three general stages (adapted from Brady 1974).

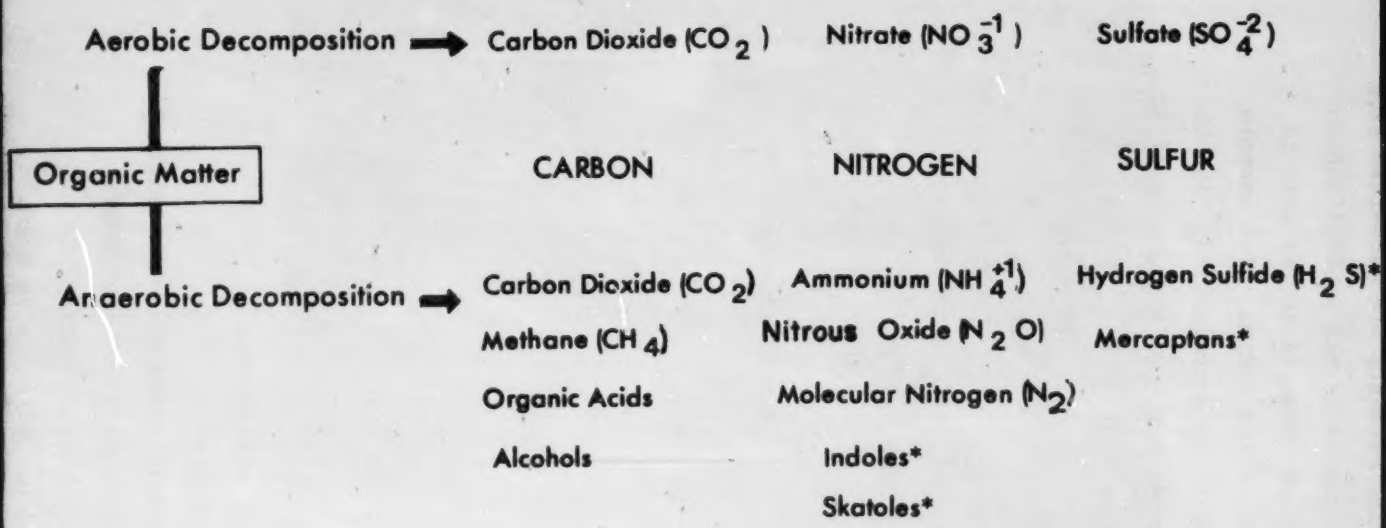
The organism numbers ultimately decline to about the same level as before the addition of fresh organic material. This marks the final stage of organic matter breakdown during which the humus itself is slowly degraded by highly specialized organisms. In natural systems that receive localized or periodic additions of organic matter, these three stages may overlap with several processes occurring simultaneously.

In the final stage of biological treatment, humus is degraded by highly specialized organisms.

The rate at which organic matter decomposition occurs and the exact nature of the intermediate and end products depends in part on the composition of the added organic material. Soil factors, however, exert considerable control as well. The presence or absence of oxygen, more than any other single factor, determines the rate and end products. The oxygen status of the soil is a function of soil porosity, and properties that favor rapid transmission of water also favor oxygen movement unless the soil is completely saturated. The presence of adequate oxygen gives rise to aerobic conditions while its lack results in anaerobic conditions. Decomposition proceeds in either case, but the rate and nature of products formed differ markedly (Figure 15).

The presence or absence of oxygen in soil largely determines the rate at which organic matter decomposes and the end products that are formed.

Under aerobic conditions, up to 60% of the organic carbon may be respired by organisms as carbon dioxide in the initial stage of decomposition. Much of the remaining carbon is incorporated into microbial cells and some of this is subsequently respired when the population declines. Anaerobic decomposition also produces some carbon dioxide along with methane (CH_4). However, the bulk of carbon, perhaps 70%, remains in partially decomposed intermediates such as organic acids and alcohols (Miller, 1973). Since relatively few organisms can degrade these products in the absence of oxygen, they accumulate. Methane, however, is one of the ultimate products if these intermediates are anaerobically decomposed.



*Objectionable Odor

FIGURE 15. Products of aerobic and anaerobic decomposition of organic matter.

Through organic matter decomposition, nitrogen, phosphorus, sulfur, and a host of other trace elements are converted from organic to inorganic forms, a process termed mineralization. The form and fate of many of these elements in the soil is determined by the oxygen status of the medium. For example, mineralized nitrogen first appears as ammonium (NH_4^{+1}). Under aerobic conditions, NH_4^{+1} is rapidly transformed by specific microbes (nitrifying organisms) into nitrate, a highly mobile anion which can easily be leached to groundwater. Under anaerobic conditions nitrate is not formed and so ammonium accumulates. By alternating aerobic and anaerobic conditions, nitrate may form and then be converted to nitrous oxide (N_2O) and/or molecular nitrogen (N_2), both gases. This latter transformation is termed denitrification. By a somewhat similar means, sulfate (SO_4^{-2}), a product of aerobic decomposition, is transformed to hydrogen sulfide gas (H_2S) under anaerobic conditions.

Many of the elements which are mineralized during organic matter decomposition and are then subject to inorganic transformations in the soil, may also be assimilated by plants. By definition, assimilation is the conversion of inorganic forms to organic forms within living tissue. Vegetation thus functions as a sink where waste nutrients, most notably nitrogen and phosphorus, can be effectively immobilized. When harvested, vegetation plays an integral part in the renovation or "treatment" of applied wastes. Other roles of vegetation along with specific nutrient uptake rates are discussed in Module 7, "Vegetative Cover".

By alternating aerobic and anaerobic conditions at the treatment site, denitrification will occur. Trace elements will be converted from organic to inorganic forms to be assimilated by plants.

Limitations of Biological Mechanisms

Organic matter is continuously added to soils as plant residues and is continuously oxidized by soil organisms. As organic additions increase, soil respiration also increases until a maximum rate of oxidation is reached. Continued increases beyond this point result in the accumulation of organic materials. Although the rate of organic carbon oxidation in soils is known to be high,

limitations for wastewater and sludge additions are not well established. Jewell (1976) recently reported, however, that a soil system, previously acclimated to highly organic wastewater from a vegetable processing facility, could degrade organics at a rate exceeding 5000 lbs/acre-day. In light of these results, it appears likely that other factors such as soil permeability and nitrogen control will limit waste application rates long before maximum organic loading capacities are reached.

Soil permeability and nitrogen content will limit waste application rates long before the maximum loading capacity for organics has been reached.

The capability of soil organisms to manipulate nitrogen additions therefore takes on added importance. Considerable attention has been focused on the conversion of nitrate to gaseous forms under anaerobic conditions. No existing system receiving domestic sewage, however, has been shown to remove more than about 30% of the total nitrogen by this process. Specific site modifications, such as drainage and recycling high nitrate percolates, have been verified in experimental work but have yet to be proven economic or needed in full-scale application. For the present then, it appears that the most reliable method for nitrogen control is crop management and N removal by plant uptake. Reliance on cropping for nitrogen control will limit the total N application rate to about 100-500 lbs/acre-yr depending on specific crops and management techniques.

No land treatment site has yet been able to remove more than 30% of the applied nitrogen by converting nitrate to gaseous forms under anaerobic conditions. The main method for nitrogen removal is still crop management and plant uptake.

Nitrogen is Major Limiting Factor in Operation of Site

Table 4 summarizes limitations for waste additions to soil. There are always exceptions to general rules, however, and these data are useful only in estimating gross land area requirements to determine the feasibility of adopting a land application alternative. Specific site conditions will often modify all of these values. For further discussion of site selection, see Module 2, "Site Evaluation".

Table 4

Summary of General Limitations for
Waste Application to Soils

Constituent	Limitation
Organics	
BOD_5	4,000 lbs/acre per application period*
SS	600 lbs/acre per application period*
Nutrients	
P	150-300 lbs/acre-yr
NH_4^{+1}	100 lbs/acre per application period*
Total N	100-500 lbs/acre-yr
Toxic Materials	
Zinc, Copper, Nickel, Cadmium	Relate to Soil Cation Exchange Capacity**
Sodium	SAR < 10

*It is assumed that the waste application period is followed by a drying period of at least 3-5 days.

**See Table 3, page 32.

A representation of computed land area requirements based on various factors is shown in Figure 16. Based on the relative land areas required, nitrogen is most often the controlling design parameter. When wastes are applied over the area required for nitrogen, an added degree of safety occurs in terms of the loading rates of other constituents. For example, if the nitrogen area requirement is fifteen times that for toxics, this reflects a fifteen-fold safety factor in the application area for toxics.

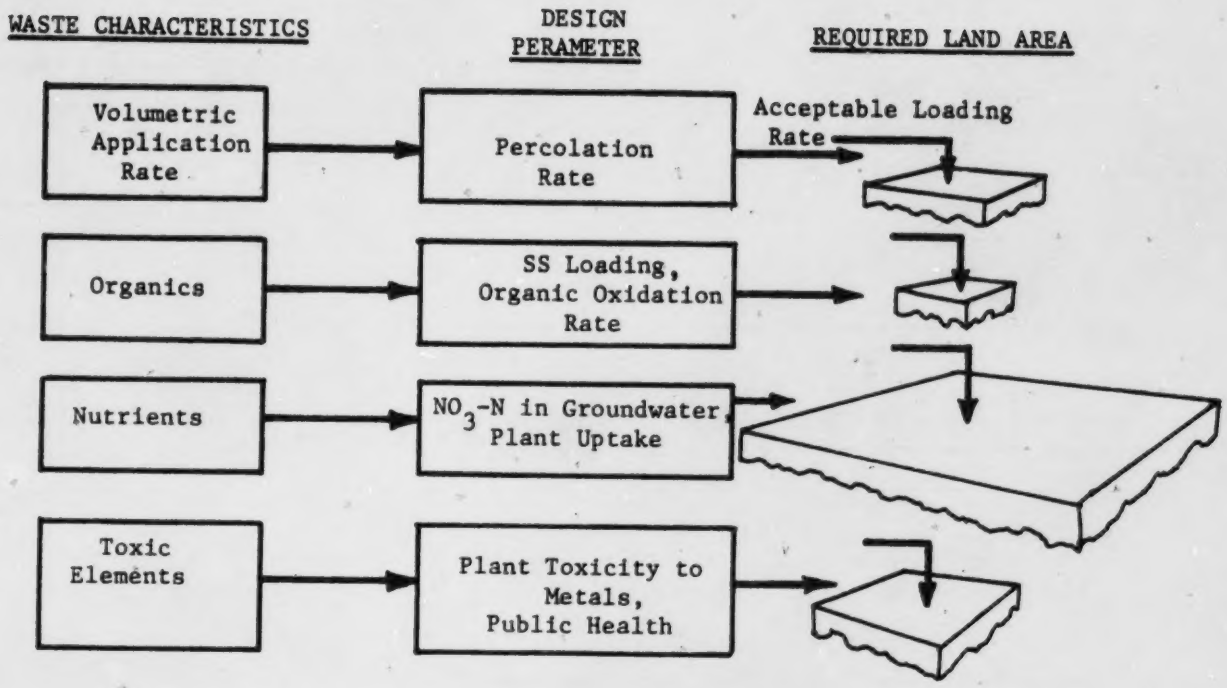


FIGURE 16. Example of relationships between waste constituents and limiting design parameters for land application systems.

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SOIL AS A TREATMENT MEDIUM

Objectives

Upon completion of this module, the participant should be able to indicate:

1. The makeup of soil, i.e., the constituents.
2. What makes a soil suitable for rapid infiltration, irrigation, or overland flow in terms of texture and structure.
3. The importance of the organic portion of the soil in land treatment.
4. What the cation exchange capacity is and its importance to land application.
5. The importance of available water capacity for land application.
6. Why an engineer cannot look only for land with a high cation exchange capacity when choosing a site for land application.

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Script to Accompany the A-T

SOIL AS A TREATMENT MEDIUM

Module 3

January, 1978

SOIL AS A TREATMENT MEDIUM

This is the A-T portion of a two part module concerning soil and its characteristics that make it a suitable medium for treating waste. (Slide 1) Because soil is variable there are few hard and fast rules that apply to its use for waste treatment. Decisions must be made, therefore, on a site specific basis, after thorough evaluation of the individual soil properties in conjunction with the evaluation of the waste being treated. This portion of the soils module deals with general considerations of the nature of waste treating characteristics of soils. There is also a booklet that accompanies this lesson which deals with more specific design potentials and parameters in relation to soils. The objectives for this lesson are in the envelope labelled, "Objectives". (Slide 2) Please stop the recorder and study the objectives list. You may keep the list for reference during the lesson.

Slide 3 is a representation of a vertical section of landscape extending from the surface down to bedrock. All of the material above the bedrock is technically termed the regolith. The regolith results from weathering of the underlying rock and/or deposition of material transported by gravity, wind, water, or ice. (Slide 4) The upper portion of the regolith has been altered by organisms and climatic factors. This gives rise to the more or less distinct horizontal layers termed horizons. (Slide 5) To a soil scientist, soil is only this most intensely altered zone. The horizons form the basis for differentiating and mapping individual soils. The soil scientist's soil, therefore, seldom extends more than three or four feet in temperate latitudes, although the regolith may extend for hundreds of feet. (Slide 6)

With this in mind, most of this tape will concern the upper few feet of soil because most soil research has been conducted for this biologically active zone. For purposes of waste treatment, however, it is convenient to use the term soil to include the entire regolith since much or all of the unconsolidated material can be instrumental in waste treatment. (Slide 7)

Soil consists of a solid matrix interspersed with pore spaces as indicated in Slide 8. The solid matter consists of both mineral particles and organic matter or humus derived from the decay of plant and animal tissue. (Slide 9) A soil rich in organic matter is critical for several

aspects of land application. As will be seen later, organic matter is important in the maintenance of soil structure, permeability, and waste treating capacity. Organic matter comprises about four to ten percent of the soil solids.

Slide 10 indicates the proportions of soil components in the surface, or plow layer, of a representative agricultural soil. The pore space is about equally divided between air and solution unless the soil is very wet or very dry.

It must be stressed, however, that soil is highly variable both in space and time. For example, the amount of organic matter changes markedly with depth as does the size and arrangement of mineral particles. Likewise, the relative proportions of air and solution fluctuate widely in accordance with climatic events and land use. In order to evaluate soil as a medium for waste treatment, it is therefore necessary to further characterize soil variability.

Slide 11 shows three different profiles, each to a depth of four feet. In the box that contained this lesson are three photographs of actual soil profiles that are similar to the ones represented in the slide. Try to characterize the differences among the three soils in terms of texture, granular structure, and other ways. The graphic representation will be utilized throughout this lesson to indicate variations among soils and the consequences of the variations for land treatment of wastes. (Slide 12) Do not hesitate to turn off the tape and refer to the photographs. In the graphic representation the alternately banded scale to the right of each profile delineates the horizons or layers in a soil profile. One of these profiles represents a soil suitable for rapid infiltration, another for irrigation, and the final one for overland flow. The differences among these soils will become clear as we proceed through this module. The distinctions that allow a soil to be suitable for a specific treatment technology are based on texture, structure, permeability, available water capacity, and cation exchange capacity. (Slide 13) Each of these will be discussed.

Soil texture (Slide 14) refers to the coarseness or fineness of the individual mineral particles. Various systems are in use today to categorize mineral particle size. Slide 15 indicates three of the systems and their relationships. Within the USDA system, soils are given textural class names

based on the relative amounts of sand, silt, and clay in the surface layer as shown in Slide 16. By definition, sandy soils are those in which sand makes up 70% or more of the material by weight. (Slide 17) A clayey soil must contain at least 35% clay. Loamy soils contain various mixtures of sand, silt and clay, between these extremes.

The textural class name assigned on the basis of the surface texture does not necessarily reflect conditions deeper in a soil profile. The texture variability, along with structure, which will be discussed next, is particularly important in determining water transmission rates.

As wastewater moves through soil, the suspended solids are removed through two mechanisms, both of which are related to soil texture. The larger solids are removed through simple blockage. (Slide 18) Both bacteria and viruses are small enough so that based on size alone, movement through the pores of many soils could be expected. These smaller solids are removed by adhering to the soil solids. It appears that most wastewater pathogens are removed in the upper few feet of all but the very coarse textured soils. (Slide 19) The distance for effective removal depends upon hydrologic loading and the soil texture. When loading rates are such that much of the applied water is held in the soil, the removal occurs mainly in the wetted zone. Further information on this topic can be found in the Pathogens module. (Slide 20)

Soil structure (Slide 21) refers to the organization of individual particles into clumps or aggregates. Slide 22 indicates some of the types of soil structure. Sandy soils tend to be relatively structureless, particularly below the surface layer. As the percent of silt and clay increases, however, particle aggregation occurs, forming units that range from weak to stable, small to large, and simple to complex. The diagrams in Slide 23 of the basic structural types, indicate the general effect of the different structures on water transmission, and where the structural type is usually found in a soil profile.

A soil profile may be dominated by a single kind of structure although usually a number of different types are encountered with depth depending on the texture and organic matter content.

Note the occurrence of granular structure in the surface layers of all three profiles shown in Slide 24. Granular aggregates result from the presence of organic matter. Notice the difference in the two soils

shown in Slide 25. Granular structure is highly desirable, particularly in loamy and clayey soils where it improves the air and water transmission capability. Granular structure, more than any other type, can be maintained or destroyed by management practices. (Slide 26)

Blocky and prismatic aggregates generally occur well below the surface and are less affected by management practices. Both of these structural units, however, are affected by moisture. Depending upon the type of clay present, the aggregates may swell upon wetting, forming a tight and nearly impermeable mass. (Slides 27-30) This is shown in this slide series, in which one type of clay was added to water resulting in a swollen, impermeable mass. On the other hand, upon drying, shrinkage cracks between the individual aggregates may allow rapid downward movement of water as would happen with the clay soil shown in Slide 31.

Permeability, (Slide 32) a property determined by the soil pores, refers to the case with which water and air are transmitted through the soil. Conditions which favor the transmission of water, however, will generally also favor the movement of air unless the soil is saturated, that is, unless all the pores are filled with water. In this section we will concentrate, therefore, on the permeability of water while realizing that the principles also refer to the permeability of air.

Permeability is quantified in terms of the rate of water movement through a unit cross section of saturated soil in unit time and is commonly expressed in inches per hour. The permeability classes, shown in Slide 33 have been defined for use in describing and interpreting soils.

Although exceptions do exist, fine textured soils generally possess slow or very slow permeability while values for coarse textured soils range from moderately rapid to very rapid. This can be seen by studying Slide 34. A medium textured soil such as a loam or silt loam tends to have moderate to moderately slow permeability. Notice that the amount of pore space, however, is least in the sandy soil, although it has the fastest percolation rate. The reason for this seeming paradox is that permeability is more a function of pore size than pore space.

Individual pores vary in size from a few microns to several millimeters in diameter. (Slide 35) For convenience, pores are often simply divided into macropores and micropores or capillary pores. Macropores,

by definition, transmit water readily in saturated soils in response to gravity as indicated in Slide 36. In contrast, micropores retain water against gravitational force. Notice that the coarse sand in Slide 37 is dominated by macropores even though it has the least amount of pore space. It thus shows the highest overall permeability. Of the three soil profile photos included in this module, you should now be able to readily pick out the profile that is suitable for rapid infiltration, the one that is suited to irrigation and the one that is best for overland flow. In general field conditions, however, there is not always this much of a distinction between soil that is suitable for overland flow and that suitable for irrigation. Often a soil will be suitable for either of these two methods of waste application. A soil suitable for rapid infiltration, however, is characteristically different from soils suited to the other two methods of application. Note the variability in macropore space with depth. Macropore space and thus permeability are related to the texture and structure of individual soil layers. As can be inferred from Slide 38, organics promote granular structure and dominance of macropores and thus improve the permeability of fine textured soils in the surface few feet. The structure and thus the permeability of fine soils is also greatly affected by management practices.

Closely related to permeability is infiltration rate, which is defined as the rate at which water enters the soil surface. (Slide 39) Infiltration rate, expressed as inches per hour, is influenced by the permeability and moisture content of the soil. In an initially dry soil, applied water enters the soil, displaces air and gradually fills the pore space. Slide 40 indicates that the constraint is the permeability of the least permeable layer. A different topography, however, might result in the applied water travelling with the least permeable horizon and ending up as ponded water near the site as shown in Slide 41. This latter result must be controlled, and monitored at a land application site to assure effective treatment. Infiltration rate thus depends upon permeability within the soil profile and topography.

These slides indicate several very important concepts for land application systems. (Slide 42) The macropores in a saturated soil will drain by the force of gravity alone in about a day as shown in Slide 43. The water that is left in the soil is in the micropores and is held through capillary action. (Slide 44) This is the point called field capacity.

Most of this water is available to plants and is extracted from the soil by the roots. Another portion of the water in the micropores is lost through evaporation. There is a point when the water in the micropores is held too tightly for use by plants. This point is called the permanent wilting point and is indicated in Slide 45. Even at the permanent wilting point there is a small amount of moisture remaining as a film around the soil solids, but this moisture is essentially unavailable to plants. The available water capacity, expressed as inches of water per some unit of depth, is that amount of water which is held in the soil between field capacity and the permanent wilting point. (Slide 46)

The available water capacity depends upon micropore space, which in turn depends upon texture, structure, and organic content of the soil. The graph in Slide 47 relates texture to the available water capacity. The sand has the least amount of micropore space and thus the smallest available water capacity. With very fine soils the increase in micropore space produces little increase in available water capacity because of the greater amount of unavailable water. Organic matter in the soil also affects the available water capacity. Slides 48 and 49 show the wetted front that results when equal amounts of water are added to a soil high in organic matter and to one that is low in organic matter. Notice how much more moisture per unit volume the high organic soil holds.

Slides 50, 51, and 52 indicate the three soil profiles again. Most of the available water capacity of the sandy profile is due to the organics in the uppermost layer of the sand.

Land application using irrigation methods depends to a great extent upon the retention time of the wastewater in the soil. The available water capacity is a guide to application limits for maximum treatment. Slide 53 indicates the ideal amount of water that can be applied. The water held in the micropores is being continually depleted by plant absorption and through evaporation. This depletion depends upon the climate and the type of vegetation.

Up to this point our principal concern has been those properties of soil which determine water transmission and retention. (Slide 54) Moving with the water, however, are several different ions. Somewhat like water, these ions are alternately retained and transmitted through the soil.

The clay and humus fractions of soils are primarily responsible for their retention. Both clay and humus are characterized by an extremely small particle size and the presence of an electrical charge as shown in Slide 55. The surface area indicated in the slide contrasts with a surface of about ten to fifty square centimeters per gram for coarse sand. The significance of the charge is that oppositely charged ions or compounds are attracted and held on the colloidal surface. The attracted ions are overwhelmingly cations because of the generally negative charge of the colloid. The cation exchange capacity is a measure of the ability of a soil to retain cations such as sodium, calcium, and potassium. Indirectly, however, the CEC serves as a rough index of all reactions which occur between charged pollutants and colloidal surfaces. In general, the greater the CEC of a particular soil, the greater the potential for effective waste treatment.

Although the cation exchange capacity indicates a soil's ability to hold cations, when all concentrations of cations are equal, the soil has a greater intensity for some than for others. Slide 56 indicates the relative intensity of attraction between the colloidal surface and the more common soil cations.

Slide 57 indicates, as an example, a system that is in dynamic equilibrium. With the equivalent amount of sodium and calcium in the system, the calcium will dominate the charged sites. Although some cations are released into solution from the solid phase and others move in to replace them, the overall proportion of the two cations in solution remains the same. If there is an influx of sodium into the system (Slide 58), the exchanges on the colloid phase will tend to favor the replacement of calcium by sodium, the greater concentration, overcoming the differences in attraction. At this point a new dynamic equilibrium point will be established as in Slide 59.

It must be emphasized that when one cation is removed from wastewater by cation exchange there must be a simultaneous release of some other cation into solution.

Slide 60 indicates that the CEC of colloids varies with type and size. Because of its dependence upon clay and humus content, the CEC can be expected to vary both within and among soil profiles. Notice the

cation exchange capacity of the organic colloid. From Slides 61, 62 and 63 it can be seen that soils with the highest water transmitting capabilities have the lowest potential for effective waste treatment as indicated by the cation exchange capacity. Soils with moderate to high CEC's offer the possibility of installing artificial drainage systems to improve water transmission and become excellent waste treatment sites. (Slide 64)

This tape has reviewed some of the basic properties of soil that are of importance in waste treatment. The booklet that follows this tape indicates the use of those properties and the loading levels that can best exploit the treatment capabilities of the soil. (Slide 65)

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Booklet to Accompany the A-T
SOIL AS A TREATMENT MEDIUM
Module 3
January, 1978

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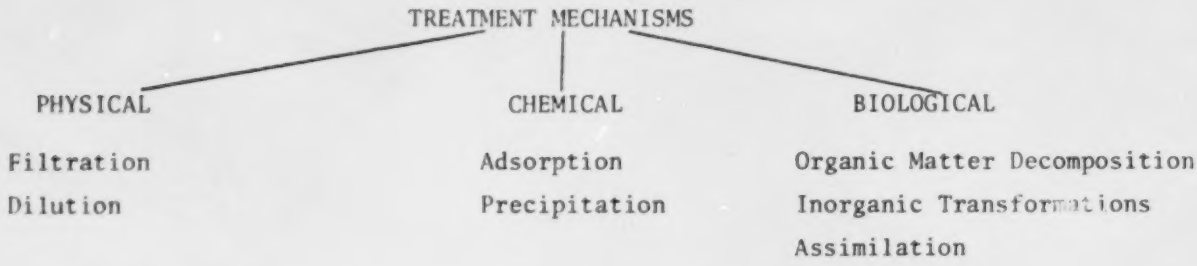
This booklet is intended to accompany the audio-tutorial lesson, "Soil as a Treatment Medium". Waste treatment mechanisms that occur in soils can conveniently be categorized as physical, chemical, and biological. Within each category, various processes act to remove or alter specific waste constituents.



As wastewater moves into and through soil pores, suspended solids are partially removed by mechanical filtration. When loading rates are such that much of the applied water is held in the soil, additional removal can occur as suspended materials settle out or adhere to the surfaces of soil particles.

Applied wastewater may be diluted either upon entering the groundwater or by augmentation in the soil with natural rainfall or snowmelt. The dilution process is furthered by chemical and biological removal of dissolved waste constituents. The reverse of dilution -- concentration-- losses are high.

Suspended Solids Can Clog Soils

Suspended materials can clog soil pores and severely reduce the infiltration rate. If such clogging is likely, there should be strict requirements for pretreatment control of suspended solids (SS). From the limited information available, however, it appears that other waste constituents such as nitrogen will limit waste applications before any significant negative effects of suspended solids are encountered.

Useful information on physical clogging of soils comes from work on sand filtration in conventional sewage treatment systems. Sand filters effectively trap fine suspended solids from secondary effluents in the first few inches of filter depth. With high loadings of suspended solids, there is generally a rapid decrease in hydraulic conductivity

over a period of 24 hours or less. Application periods must then be followed by a backwash (reversing flow direction) to remove the clogging particles.

In contrast, land application systems can recover from clogging through natural decomposition of the suspended solids during non-application or resting periods. Furthermore, the most common suspended solid loadings to land are far less than those used in conventional sand filtration. Two inches of effluent per week applied to the land would add less than 5,000 pounds of suspended solids per acre per year.

A general rule of thumb is that the maximum continuous application rate for septic tank effluent on soil is about 5% of the percolation rate as measured with clean water. This may well be too conservative for systems which allow for drying and recovery. Figure 1 illustrates the recovery capability of soil when allowed to rest in an aerobic state after successive periods of flooding with septic tank effluent.

From these data, it appears that application scheduling and relatively simple pretreatment such as screening or primary sedimentation should be adequate to avoid excessive clogging.

Chemical Reactions Alter Mobility of Waste Constituents

Chemical reactions among dissolved ions or compounds, and interactions with the soil solid phase alter the mobility of waste constituents. Some dissolved constituents are retained within the profile indefinitely while the movement of others is only temporarily restricted or unaffected.

Two closely related chemical processes, adsorption and chemical precipitation, account for most of the retention. Adsorption, as a loosely applied term, refers to the net effect of interactions between dissolved ions or compounds and the surfaces of clay and humus particles. Precipitation is the formation of an insoluble or slowly soluble product from constituents that were originally in solution. In many cases, the two processes are indistinguishable.

Ion exchange is one type of adsorption process. A distinction is made between anion exchange which involves negatively charged ions or compounds and cation exchange which involves positively charged ions or compounds. Under acid conditions -- pH less than 5 -- some soils are able to hold small amounts of anions such as nitrate, sulfate, and phosphate in an exchangeable form. Anion exchange, however, is of minor importance in land application. Phosphorus is the only anion appreciably retained in soils, though the primary mechanism is not anion exchange.

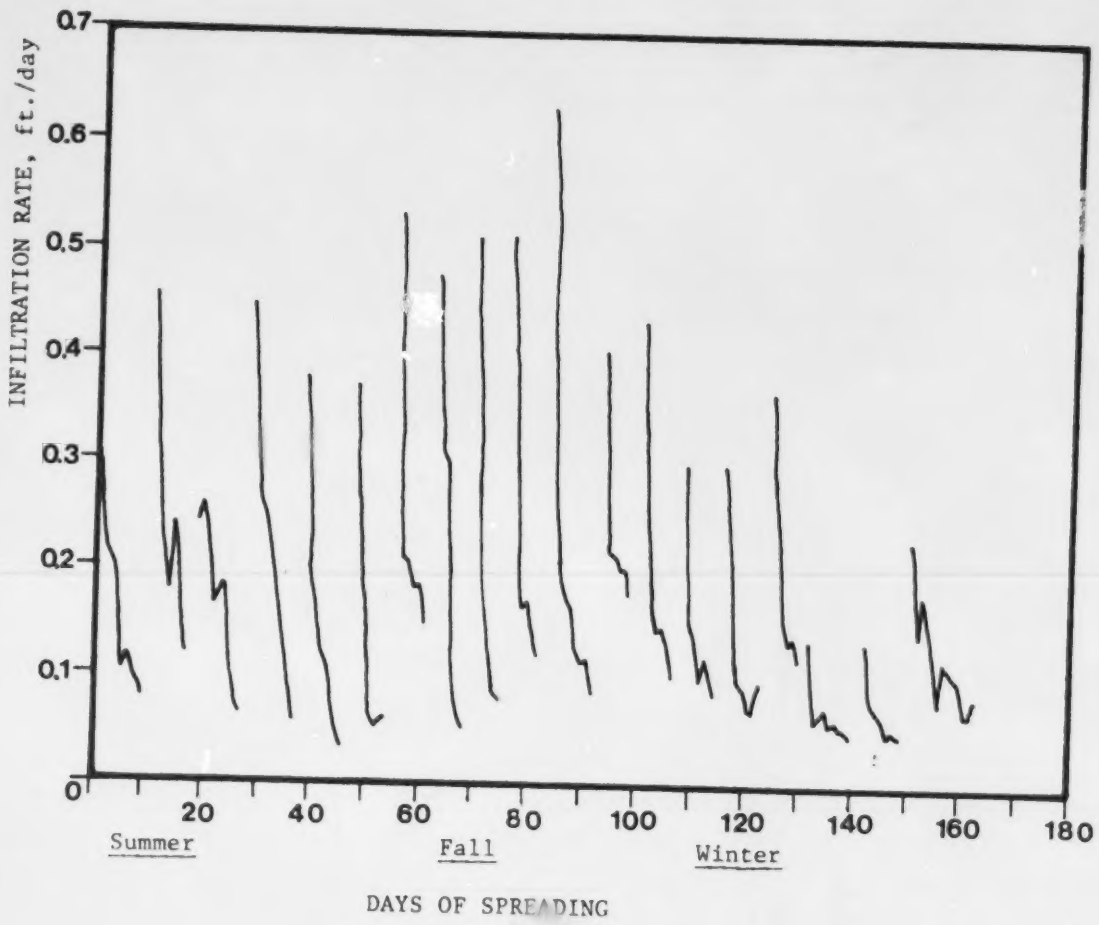


FIGURE 1. Recovery of infiltration rates in a Yolo loam soil after intermittent applications of primary sewage effluent (after McGauhey et al. 1966).

The predominant ion exchange reactions in most U.S. soils involve cations. The magnitude of cation exchange properties in soil is measured by the cation exchange capacity (CEC), a term introduced in the A-T section. Cation exchange is a function of both the relative intensity of attraction between ion and colloidal solid, and of the relative concentrations of exchangeable ions present in the soil solution.

The relative intensity of attraction between soil colloids and the more common soil cations is shown below:

$$Al^{+3} > H^{+1} > Ca^{+2} = Mg^{+2} > K^{+1} \gtrsim NH_4^{+1} > Na^{+1}$$

(Aluminum) (Hydrogen) (Calcium) (Magnesium) (Potassium) (Ammonium) (Sodium)

Consider a closed system consisting of a solid colloidal phase and a solution phase (Figure 2). Within the system assume equal amounts of calcium and sodium, distributed between the two phases. At any given instant, some cations are released into the solution from the solid phase and others move in to replace them. The system is said to be in dynamic equilibrium when these random exchanges occur without altering the overall proportion of the two cations in solution or on the solid phase. Because of the greater intensity of attraction between calcium and the colloidal surfaces, Ca^{+2} will dominate the charge sites at equilibrium.

Assume now there is an influx of sodium into the system (Figure 3). Due to the much greater concentration of Na^{+1} in solution, random exchanges on the solid phase now favor the replacement of Ca^{+2}, despite its greater intensity of attraction. Therefore, at equilibrium, Na^{+1} will likely occupy the greater number of charge sites. Similarly, in wastewater treatment systems, the retention of dissolved cations depends largely on their concentration in the solution entering the soil.

The reaction in which sodium replaces some other cation is especially important. A dominance of sodium on the soil colloids weakens the stability of soil aggregates causing dispersion and swelling. This in turn decreases the macropore space and thus sharply reduces permeability.

Exchange reactions involving ammonium (NH_4^{+1}) are also of special interest, since they offer one means to retain nitrogen at least temporarily. Such retention allows time for biological processes to transform ammonium to nitrate, (NO_3^{-1}), a highly mobile ion.

Exchangeable cations are replaceable. Thus, when sodium, ammonium, or any other cation is removed from wastewater via cation exchange, there must be simultaneous release of some other cations into solution. The net effect is, therefore, some readjustment in the composition of the exchanger and solution phases, but the total soluble salt concentration does not change appreciably.

Specific Adsorption Refers to Tight Retentions

Soils have a variable capacity to retain certain cations and anions so tightly that they are not exchangeable, a process called specific adsorption. Like ion exchange, specific adsorption occurs between ions or compounds in solution and the solid colloidal phase. For example, orthophosphate anions ($H_2PO_4^{-1}$, HPO_4^{-2}) react on the surfaces of iron and aluminum containing clays. Initially, this phosphate may be exchangeable with other anions but with time it becomes more and more tightly bound.

Many of the heavy metal cations such as zinc, copper, nickel, cadmium, mercury, lead, and chromium are present in wastewaters at concentrations too low to be appreciably affected by cation exchange reactions. However, these cations seem to be incorporated into the soil solid phase in a non-exchangeable form. The actual reversion mechanisms are poorly understood.

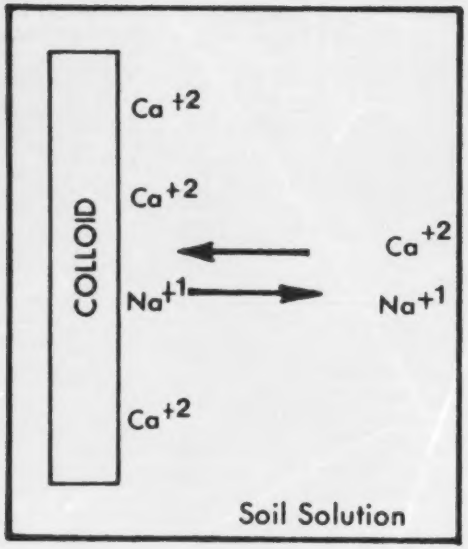


FIGURE 2. The intensity of attraction between soil colloids and specific cations influences the cation exchange process; Ca^{+2} is more strongly attracted and thus dominates the colloidal charge sites.

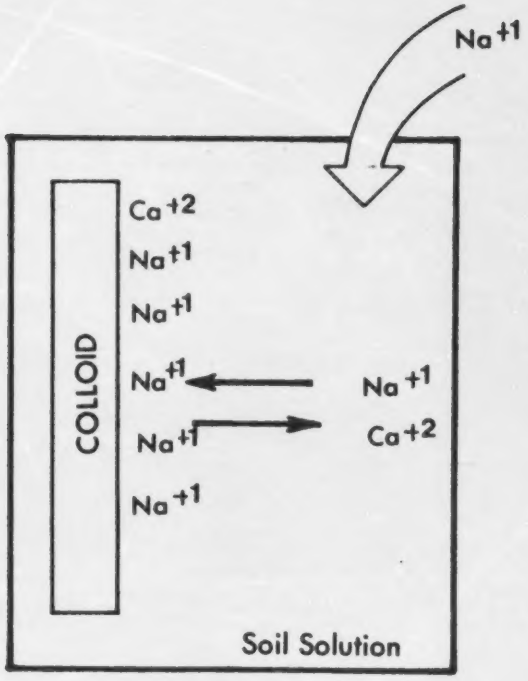


FIGURE 3. Concentration can offset the effect of intensity of attraction; although Ca^{+2} is more strongly attracted, the greater concentration of Na^{+1} enables it to dominate the colloidal charge sites.

The effectiveness of soil in the removal of waste constituents either by ion exchange or specific adsorption depends on contact between dissolved substances and the appropriate colloidal phases. Contact depends largely on the degree to which a soil is uniformly wetted. Initially, only the external surfaces of aggregates are in direct contact with wastewater. Over the longer term, internal surfaces tend to equilibrate with constituents held on external surfaces. Thus, the length of time that the water remains in the soil affects the amount of waste constituents that can be removed from the water. This is important in determining application rates and the frequency of rest periods. Over extended periods, the adsorption capability may be rejuvenated through reversion processes.

The chemical mechanisms discussed thus far have involved the interaction of dissolved constituents and the solid colloidal phase in the soil. Many ion species react within the solution phase itself, resulting in the formation of insoluble or slowly soluble precipitates. The point at which chemical precipitation occurs depends on the concentration of the participating ions as defined by their solubility product constant (K_{sp}). The solubility product constant is obtained by multiplying together the molar concentration of reactants (moles/l) in a saturated solution.

$$K_{sp} = [A] \cdot [B]$$

where, $[A]$ = molar concentration of ion A (moles/l)

$[B]$ = molar concentration of ion B (moles/l)

For example, the K_{sp} value for calcium sulfate ($CaSO_4$) is 2.4×10^{-5}. This means that whenever the concentration of the sulfate ion times the concentration of the calcium ion exceeds 2.4×10^{-5}, $CaSO_4$ will precipitate out of solution. Suppose the sulfate concentration in applied wastewater was 125 mg/l. This can be converted to moles/l as follows:

$$\text{grams/mole } SO_4 = \text{at.wt. S} + 4(\text{at.wt. O})$$
$$= 32 + 4(16)$$
$$= 96$$
$$\frac{125 \text{ grams} \times 10^{-3}/\text{l}}{96 \text{ grams/mole}} = 1.3 \times 10^{-3} \text{ moles/l}$$

Using the solubility product constant the concentration of calcium in the solution which would cause $CaSO_4$ to precipitate out of solution can be found.

$$K_{sp} = [Ca^{+2}] \cdot [SO_4^{-2}]$$

$$2.4 \times 10^{-5} = [Ca^{+2}] \cdot [1.3 \times 10^{-3}]$$

$$[Ca^{+2}] = \frac{2.4 \times 10^{-5}}{1.3 \times 10^{-3}}$$

$$= 1.85 \times 10^{-2} \text{ moles/l}$$

This can be converted back to mg/l by multiplying the moles/l by mg/mole:

$$\text{mg } Ca^{+2}/l = (1.85 \times 10^{-2} \text{ moles/l}) \cdot (40 \times 10^{3} \text{ mg/mole})$$

$$= 740$$

If the wastewater contained 730 mg/l of Ca^{+2} and after entering the soil, evaporation caused the wastewater to become more concentrated, the product of Ca^{+2} and SO_4^{-2} would exceed the K_{sp} value and the reaction below would proceed to the right, forming insoluble $CaSO_4$.

$$Ca^{+2} + SO_4^{-2} \rightleftharpoons CaSO_4 \downarrow$$

The addition of rainwater and/or removal of reactants by ion exchange, specific adsorption or other means would tend to dilute the solution driving the above reaction to the left. Under such conditions, the solid phase $CaSO_4$ dissolves.

In general, the concentrations of dissolved constituents in the soil solution cannot exceed the concentration defined by their solubility produce constant. However, two notable exceptions exist. The first occurs in cases where the formation of a precipitate proceeds very slowly. For example, although varasite $[Al(H_2PO_4)(OH)_2]$ is highly insoluble in soil ($K_{sp} = 3 \times 10^{-31}$), its formation may take weeks or even months. This reaction is one of many which account for the long-term retention of phosphorus in soils. The second exception is due to formation of organic complexes (chelates). These react with certain ions, usually cations to form non-ionic soluble complexes. As an example, certain soluble organic compounds can incorporate heavy metal cations into their structure. The metals thus remain in solution but are not subject to chemical precipitation reactions. In effect, the formation of such

complexes reduces the soil's ability to retain heavy metals through precipitation reactions.

Chemical Mechanisms are limited

What is the soil's capacity to "treat" toxic elements and nitrogen and phosphorus?

Many of the toxic elements such as copper (Cu), and nickel (Ni) are positively charged and their retention in soil is related to the cation exchange capacity.

Several years ago, the focus on phosphorus removal from wastewater caused renewed interest in land application for this purpose. Agricultural experience had already shown that efficient phosphorus retention occurred in soils, but limitations of this removal capacity were not clear. Current knowledge indicates that phosphorus removal down to a strict 0.05 mg/l can be achieved over site lifetime of 20 years or more at annual loading rates of at least 150 lb P/acre-yr., and perhaps twice this amount. Only the high-rate rapid infiltration systems exceed this rate of loading. However, efficient removal can only be achieved where intimate contact between wastewater and the soil is achieved. High efficiency P removal should therefore not be expected in overland flow systems.

Nitrogen loading constitutes the major limiting factor for most land application systems. The chemical mechanism of most significance to nitrogen is the reaction of positively charged ammonium ions with the soil cation exchange complex. For a soil with a CEC of 15 meq/100 g, about 100 lb. of ammonium - nitrogen can be retained in this way before saturation is reached. In comparison, a two-inch application of unnitrified effluent would commonly add no more than about 16 lb/acre of ammonium - nitrogen. Ammonium retention is a useful control mechanism on a short-term basis, but is of little long-term value since the ammonium ion is biologically converted to nitrate, a readily leached form of nitrogen.

As noted earlier, the accumulation of sodium on the soil exchange complex can lead to a degradation of soil structure and thus a sharp reduction in infiltration and permeability rates. The sodium limitation of a wastewater is often expressed in terms of the sodium adsorption ratio (SAR). The SAR is defined as:

$$SAR = \frac{[Na^{+1}]}{\sqrt{\left(\frac{[Ca^{+2}] + [Mg^{+2}]}{2}\right)}}$$

where the concentrations of sodium, calcium, and magnesium are expressed in millequivalents per liter (meq/l).

[NOTE] $\frac{\text{mg } Na^{+1}/l}{22.99} = \text{meq } Na^{+1}/l$; $\frac{\text{mg } Ca^{+2}/l}{20.04} = \text{meq } Ca^{+2}/l$;

$\frac{\text{mg } Mg^{+2}/l}{12.15} = \text{meq } Mg^{+2}/l$

As a general rule, the SAR of applied wastewater should not exceed 10.

Solve this problem on sodium adsorption ratio (SAR). Evaluate the wastewater characterized below to determine if it contains a safe sodium level for application to the land.

Element	Concentration mg/l	Atomic weight
Calcium	300	40
Magnesium	200	24
Sodium	50	23

1 meq wt equals atomic weight of the ion divided by the valence.

The solution of this problem is found on page 19 of this booklet.

Biological Organisms Alter Waste Constituents

Organisms alter waste constituents through organic matter decomposition, inorganic transformations, and nutrient assimilation. Such biological "treatment" processes are largely restricted to the upper few feet of soil, sometimes termed the biologically active zone or rooting zone.

The ability of soil organisms to decompose organic compounds is a function of their population complexity. Soils normally contain a wide diversity of native organisms including many kinds of bacteria, fungi, actinomycetes, protozoa, worms, and insects along with higher plants and animals. Applied wastes usually contain additional organisms,

especially bacteria, of types which may be few or absent in untreated soils. Decomposition of complex organics proceeds step-by-step and involves many specific enzymes. Thus, the diversity of organisms enhances the capability of the soil to degrade a wide variety of organic substances.

Decomposition of newly added organic material may be envisioned as taking place in three general steps as shown in Figure 4. Initially, organisms digest the more easily decomposed material consuming oxygen and releasing carbon dioxide and water in the process. The five-day biological oxygen demand (BOD_5) measures the amount of oxygen consumed in this stage. This pulse of activity is accompanied by a rapid increase in organism numbers, which in itself may lead to a temporary clogging of soil pores.

In the second stage, organism numbers decline as the easily decomposed organic fraction is exhausted. The resulting mass of dead microbial tissue along with other intermediate decay products provide substrate for new organisms. This material, along with more resistant compounds from the original addition, the so-called refractory organics, are at least partially degraded to a relatively stable end-product, humus.

By now, organism numbers have declined to about the same level as before the addition of fresh organic material. This marks the final stage of organic matter breakdown during which the humus itself is slowly degraded by highly specialized organisms. In natural systems that receive localized or periodic additions of organic matter, these three stages may overlap with several processes occurring simultaneously.

The rate at which organic matter decomposition occurs and the exact nature of the intermediate and end-products depends in part on the composition of the added organic material. But soil factors exert considerable control. The presence or absence of oxygen, more than any

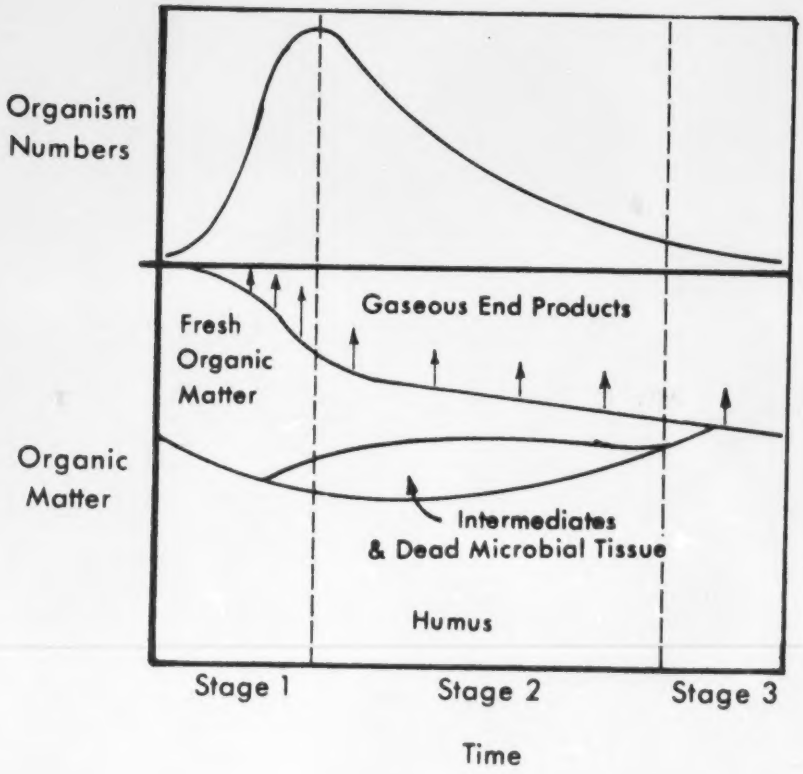


FIGURE 4. When fresh organic material is added to soil, decomposition occurs in three general stages (adapted from Brady 1974).

other single factor, determines the rate and end-products. The oxygen status of the soil is a function of soil porosity, water content, and properties that favor rapid transmission of water also favor oxygen movement unless the soil is completely saturated. The presence of adequate oxygen gives rise to aerobic conditions while its lack results in anaerobic conditions. Decomposition proceeds in either case, but the rate and nature of products formed differ markedly (Figure 5).

Under aerobic conditions, up to 60% of the organic carbon may be respired by organisms as carbon dioxide in the initial stage of decomposition. Much of the remaining carbon is incorporated into microbial cells and some of this is subsequently respired when the population declines. Anaerobic decomposition also produces some carbon dioxide along with methane (CH_4). However, the bulk of carbon remains in partially decomposed intermediates such as organic acids and alcohols. Since relatively few organisms can degrade these products in the absence of oxygen, they accumulate.

Through organic matter decomposition, nitrogen, phosphorus, sulfur, and a host of other trace elements are converted from organic to inorganic forms, a process termed mineralization. The form and fate of many of these elements in the soil is determined by the oxygen status of the medium. For example, mineralized nitrogen first appears as ammonium (NH_4^{+1}). Under aerobic conditions, NH_4^{+1} is rapidly transformed by specific microbes into nitrate, a highly mobile anion which can easily be leached to groundwater. Under anaerobic conditions nitrate is not formed and so ammonium accumulates. By alternating aerobic and anaerobic conditions, nitrate may form and then be converted to nitrous oxide (N_2O) and/or molecular nitrogen (N_2), both gases. This latter transformation is termed denitrification. By a somewhat similar means, sulfate (SO_4^{-2}), a product of aerobic decomposition, is transformed to hydrogen sulfide gas (H_2S) under anaerobic conditions.

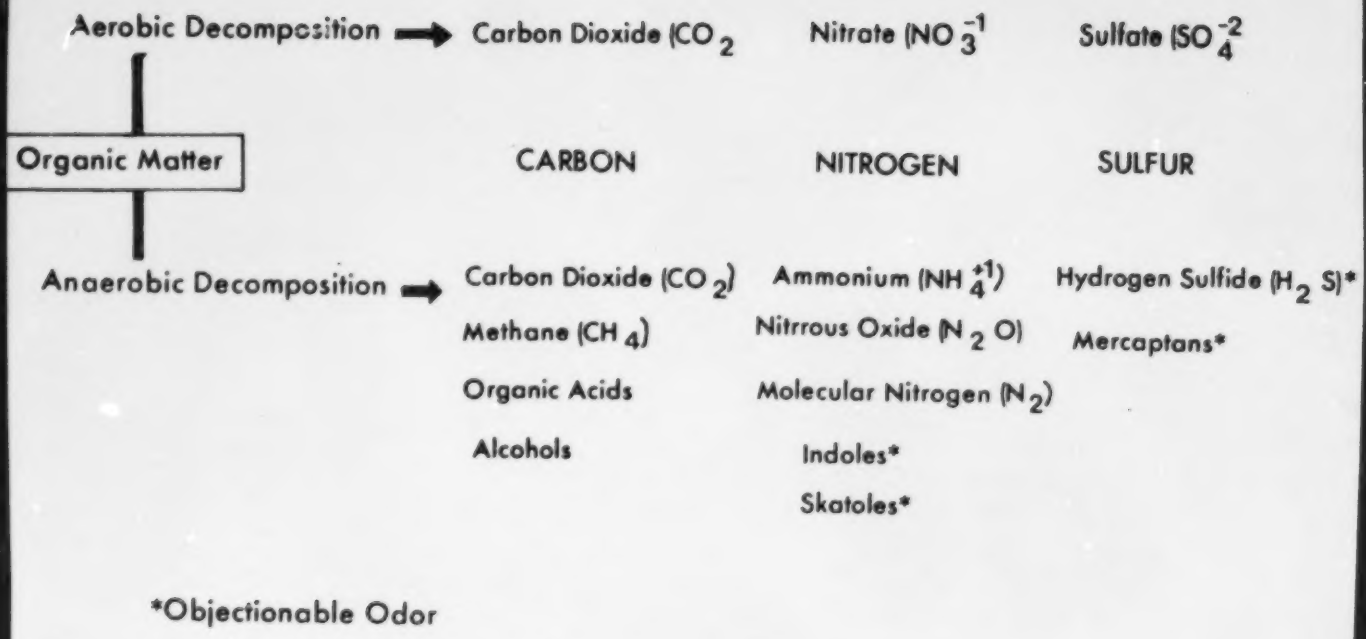


FIGURE 5. Products of aerobic and anaerobic decomposition of organic matter.

Many of the elements which are mineralized during organic matter decomposition and are then subject to inorganic transformation in the soil, may also be assimilated by plants. Assimilation is the uptake of the element by the roots and its accumulation in plant tissue - usually in organic form. Vegetation thus functions as a sink where waste nutrients, most notably nitrogen and phosphorus, can be effectively immobilized. When harvested, vegetation plays an integral part in the removal of these elements from applied wastes.

Biological Mechanisms are Limited

Organic matter is continuously added to soils as plant residues and continuously oxidized by soil organisms. As organic additions increase, soil respiration also increases until a maximum rate of oxidation is reached. Continued increases beyond this point result in the accumulation of organic materials. Although the rate of organic carbon oxidation in soils is known to be high, limitations for wastewater and sludge additions are not well established. It appears likely that other factors such as soil permeability and nitrogen control will limit waste application rates long before maximum organic loading capacities are reached.

The capability of soil organisms to manipulate nitrogen additions therefore takes on added importance. Focus has been on the conversion of nitrate to gaseous forms under anaerobic conditions. No existing conventional system receiving domestic sewage except for those specifically designed for nitrogen removal, has been shown to remove more than about 30 percent of the total nitrogen by this process. Specific site modifications, such as drainage and recycling high nitrate percolates, show promise but have yet to be proven. For the present then, it appears that the most reliable method for nitrogen control is crop management and N removal by plant uptake. Reliance on cropping for nitrogen control will limit the total N application rate to about 100-500 lb/acre-yr depending on specific crops and management techniques.

Summary of Limiting Factors

Table 1 summarizes limitations for waste additions to soil. These data are useful only in estimating gross land-area requirements to determine the feasibility of adopting a land application alternative. Specific site conditions will often modify all of these values.

Figure 6 shows relationships between waste constituents and limiting design parameters in land application. Based on the relative land areas required, nitrogen is most often the controlling design parameter. When wastes are applied over the area required for nitrogen, an added degree of safety occurs in terms of the loading rates of other constituents. For example, if the nitrogen area requirement is three times that for toxics, this reflects a three-fold safety factor in the application area for toxics.

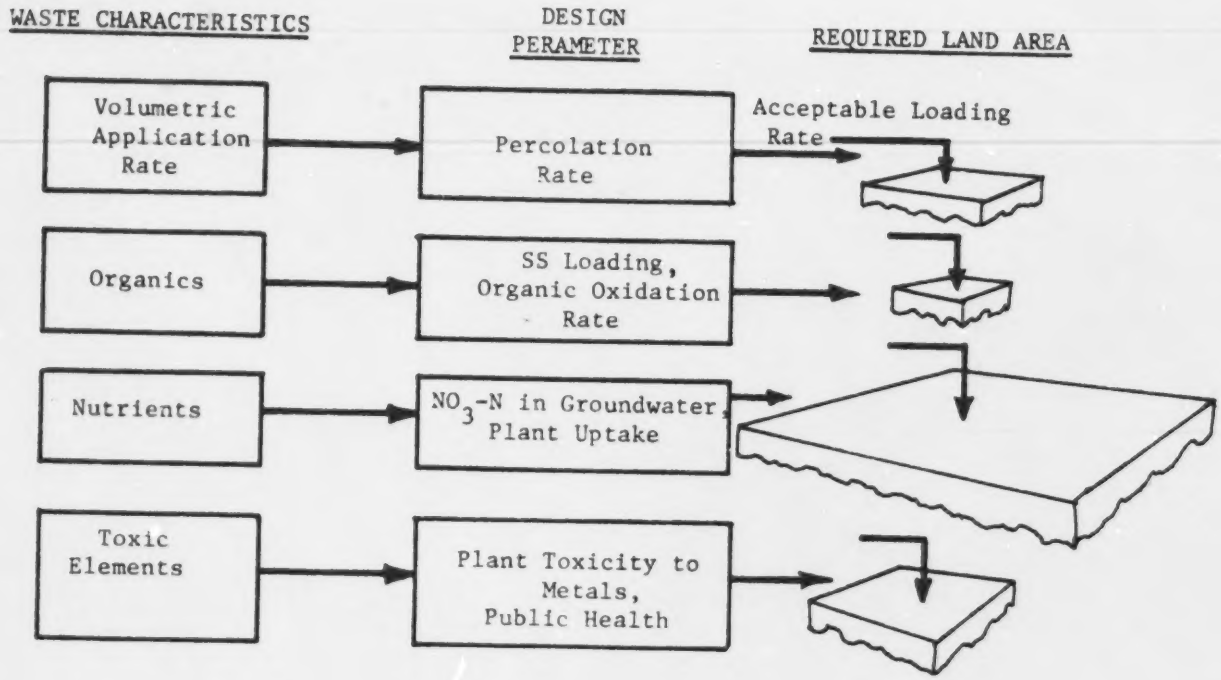


FIGURE 6. Relationships between waste constituents and limiting design parameters for land application systems.

TABLE 1. Summary of general limitations for waste application to soils.

CONSTITUENT	LIMITATION
Water	≤ 5% of percolation rate
Organics	
BOD_5	4,000 lb/acre per application period *
SS	600 lb/acre per application period *
Nutrients	
P	150 - 300 lb/acre-yr
NH_4^{+1}	100 lb/acre per application period *
Total N	100 - 500 lb/acre-yr
Potentially toxic elements such as cadmium should be removed at the source of discharge into the sewer system whenever possible. If wastes containing cadmium are applied to the land, the levels of cadmium in the crops produced should be continuously monitored. See Module 11, "Potentially Toxic Elements" for additional suggestions.	
Sodium	SAR < 10

* It is assumed that the waste application period is followed by a drying period of at least 3 - 5 days.

Answer

#1. Convert concentrations of mg/l to meq/l

$$1 \text{ meq } Ca^{+2} = \frac{40}{2} \times 10^{-3} = .020 \text{ mg } Ca^{+2}/\text{meq}$$

$$1 \text{ meq } Mg^{+2} = \frac{24}{2} \times 10^{-3} = .012 \text{ mg } Mg^{+2}/\text{meq}$$

$$1 \text{ meq } Na^{+1} = \frac{23 \times 10^{-3}}{1} = .023 \text{ mg } Na^{+1}/\text{meq}$$

$$300 \text{ mg } Ca^{+2}/1 \times \frac{1 \text{ meq}}{.020 \text{ mg } Ca^{+2}} = 15000 \text{ meq/1}$$

$$200 \text{ mg } Mg^{+2}/1 \times \frac{1 \text{ meq}}{.012 \text{ mg } Mg^{+2}} = 16667 \text{ meq/1}$$

$$50 \text{ mg } Na^{+1} \times \frac{1 \text{ meq}}{.023 \text{ mg } Na^{+2}} = 2174 \text{ meq/1}$$

Substitute into SAR formula.

$$SAR = \frac{[Na^{+1}]}{\left(\frac{[Ca^{+2}] + [Mg^{+2}]}{2}\right)^{0.5}}$$

$$SAR = \frac{2174}{\left(\frac{16667 + 15000}{2}\right)^{0.5}}$$

$$SAR = 17.3 > 10$$

This wastewater is not suitable for land application according to the general rule for SAR.